A STUDY OF THE TEMPERATURE GRADIENTS
OF GASES FLOWING THROUGH HEATED
POROUS METAL

by

Lt. Cdr. D. J. O'Meara, U.S.N.
Lt. Cdr. C. C. Andrews, U.S.N.

Thesis
O55

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Lt. Cdr. D. J. O'Meara, U.S.N.

and

Lt. Cdr. C. C. Andrews, U.S.N.

In partial fulfillment of the requirements for the degree of Aeronautical Engineer

California Institute of Technology
Pasadena, California

1947

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TABLE OF CONTENTS

8083

ACKNOWLEDGEMENT

The authors wish to express their gratitude to Dr. Pol Duwez and to Mr. H. L. Wheeler of the GALCIT Jet Propulsion Laboratory. Dr. Duwez's helpful criticism and interpretation of the data have contributed immeasurably in the preparation of this report. Mr. Wheeler interested them in the problem studied and gave invaluable guidance in the design and preparation of the equipment employed.

SUMMARY

Nitrogen and Hydrogen were passed through a pack of heated porous metal discs to obtain temperature distribution as a function of (1) mass flows and (2) temperatures at which metal was heated. An effort was made to obtain heat transfer per unit volume of porous metal as a function of (1) mass flows and (2) temperatures at which the metal was heated. By varying inlet gas pressures at various metal temperatures the effect of temperature on pressure drop was determined.

The results show that a cool gas flowing through a heated porous metal very quickly assumes the temperature of the metal. Heat transfer appears to increase linearly with mass flow up to a certain point above which the results were inconclusive. The variation of mass flow with pressure drop was determined to be linear for low pressure drop and to increase at a greater rate for higher pressure drops.

INTRODUCTION

This study was prompted by the desire to learn the effects of passing a cold gas through a uniformly heated porous metal, namely, the temperature distribution of the gas as a function of mass flow and as a function of the difference between one incoming gas temperature and various temperatures at which the metal was heated. In the investigation, however, it was realized that since the source of heat was external it was necessary that heat flow from the perimeter of the specimens radially inward which caused a temperature variation across the diameter of the specimens. This variation produced an effect in the measured results.

The investigation as carried out was very preliminary in nature due to the limitations of the equipment. It is believed, however, that this investigation provided both useful information and a stepping off place for further investigation of this important problem.

DESCRIPTION OF APPARATUS AND TEST PROCEDURE

The following listed items of equipment comprised the apparatus:

No.	Item
10	40% porous stainless steel circular discs of 3/4" diameter and 1/10" thickness.
10	Brass rings, 3/10" thickness, 3/4" inner diameter, and 2" outer diameter.
30	Garglock gaskets cut to same diameters as brass rings.
13	Iron-constantan thermocouples with glass insulation lead wires.
1	Stainless steel tube, 2-1/2" diameter, 8" in length.
1	Steel tube, outer diameter 2-1/4", inner diameter 1-3/4", length 11".
1	Steel tube, outer diameter 2-1/4", inner diameter 1-3/4", length 20".
1	3/8" standard black pipe 16-1/2" long.
1	3/8" standard black pipe 30" long.
1	Pressure regulator.
1	Pressure gage.
1	Furnace, 3.4 K.W., combustion tube type.
1	Flow meter, volumetric type.
1	Micromax complete with thermocouple.
1	Selector switch, 11 pt.
1	Potentiometer, Leeds and Northrup.
2	Steel discs, 3/8" thickness, outer diameter 2", inner diameter tapped for 3/8" pipe threads.
4	Barrier strips, 8 pt.

DESCRIPTION OF APPARATUS

The apparatus consisted of the above listed equipment so assembled to permit the flow of nitrogen and hydrogen gases through a pack of heated porous metal specimens and the recording of the required data. The brass rings (item No. 5, Fig. 25) were shrunk over the metal specimens (item No. 7, Fig. 25) to effect firm mountings for the specimens, to insure a ready heat flow to the specimens and to prevent a gas leakage between the rings and specimens. Eleven thermocouples were mounted in the garlock gaskets by spreading the gasket material apart and inserting the thermocouples radially through the opening (Fig. 29). This was found to be necessary in order to insure the correct positioning of the thermocouple beads and to prevent the thermocouple leads from causing a gas leakage. The rings were placed face to face with three gaskets on each side of each ring (one gasket on either side of the center gasket holding the thermocouple) (Fig. 25). A thermocouple was mounted in each of two metal specimens (the first and second specimens from the gas inlet end) (Figs. 25 and 29). All thermocouple leads were placed in a groove cut longitudinally along the outer side of the cylindrical pack and lead out on the gas outlet end (Fig. 28). The pack was then inserted in the stainless steel tube (item No. 4, Figure 25). Steel discs (item No. 3, Fig. 25) (of same diameter as brass rings) into which the 3/8" black pipes were threaded were then inserted at either end of the tube. The threaded steel tubes (items Nos. 1 and 10, Fig. 25) were then tightly

screwed into either end of the stainless steel tube, their ends butting against the outer faces of the steel discs. Sufficient compression of the brass rings was accomplished in this design to prevent gas leakage to at least 100 psi gas pressure. This unit made up of the three sections of tubing was then placed in the furnace as shown by photographs.

The gas was introduced into the apparatus from a standard 2500 psi bottle, through a pressure regulator valve and a cooling coil (Fig. 24). Recorded pressures of the incoming gas were read from a sensitive gage mounted at the end of the 3/8" pipe leading into the pack. The gas discharged from the pack through the 3/8" pipe mounted on the outgoing end of the pack into another cooling coil, and from there to the flow meter.

The thermocouple leads were lead through the clearance between the steel tube and the 3/8" pipe on the outgoing end to barrier strips mounted on the outer end of the 3/8" pipe. Leads from the eleven point selector switch were connected to the barrier strips and to the potentiometer permitting the ready sampling of gas and metal temperatures.

The furnace temperature was controlled by a micromax. The thermocouple indicating the furnace temperature to the micromax was inserted between the outgoing steel tube and the outgoing 3/8" pipe, and butted against the steel disc which was located approximately in the center of the furnace. Furnace temperatures recorded in results were indicated by this thermocouple.

PROCEDURE.

All data recorded were under conditions of equilibrium. The procedure, therefore, was to heat the pack in the furnace to the desired temperature while the gas was flowing at the desired rate and adjust the power input to the furnace (by a rheostat control) to maintain equilibrium conditions. Because of the long time required to change the temperature of the pack in the furnace all flow rates for one gas were taken at one furnace temperature before changing the furnace temperatures.

Because of the variable flow of heat from the pack along the entry pipe it was impractical to keep the gas inlet temperature constant for all furnace temperatures and rates of flow. Means of cooling by immersing the inlet cooling coils in CO_2 ice and blowing cold gas over the entry pipe were employed. These methods, however, proved inadequate with the apparatus used.

The heated gas discharged from the pack was cooled in a coil immersed in a container of water. Cooling was necessary due to temperature restrictions on the gas flow meter. The temperature of the gas entering the flow meter was the same as that of the cooling water.

DISCUSSION

In an effort to compare gas and metal temperatures a thermocouple was imbedded in each of the first two specimens from the inlet end of the pack. Temperatures indicated by these thermocouples were found to differ a small amount from the temperatures indicated by the thermocouples in the gas stream emerging from the specimens. These temperature differences were not determined precisely, but it was concluded that the gas temperature was of the order of from one to ten degrees lower than the metal temperature, depending, of course, on the rate of mass flow.

By varying the mass flow at constant furnace temperatures, relative temperature distributions were determined (Figs. 1 to 8). At low mass flows the temperatures of the gases were found to increase rapidly in the first few specimens and then increase at a slower and slower rate as the gas temperature approached that of the furnace. At higher mass flows the gas temperatures were found to approach the furnace temperatures at a more nearly linear rate. Final gas temperatures were higher for lower mass flows.

Two gases, nitrogen and hydrogen, were flowed through the heated porous metal pack to obtain comparative data on mass flow, temperature distribution, and heat transfer, for constant pressure drops and constant furnace temperatures. It was found that mass flows were approximately proportional to the molecular weights of the two gases. Temperature distributions for the two gases were found to be similar. Due to the limitations of the apparatus used the heat transfer data obtained were not adequate to make conclusive comparisons.

The external heating resulted in temperature variations diametrically across the specimens. Since the gas temperatures were taken at the center of the stream they were lower than average gas temperatures over a cross-section. This effect gave temperature gradient curves with less slope than would have been obtained with more nearly uniform heating.

An effort was made to determine the variation of heat transfer with mass flow at constant furnace temperatures. Heat transfer appeared to increase linearly with mass flow up to a certain point above which the results were not conclusive (Figs. 22 and 23).

Furnace Temperature = $70^{o}F$

Nitrogen Gas

Gas Inlet Pressure (psi)	Flow Rate (sec/1.0 ft^3)	Mass Flow (lb/in^2-sec) x 10^{-4}
10	313.2	4.9
20	159.3	9.64
30	104.8	14.66
40	75.9	20.2
50	57.8	26.6
60	47.2	32.5

Furnace Temperature = 400 °F

Nitrogen Gas

Thermocouple	Millivolts	°F	Millivolts	°F	Millivolts	°F	Millivolts	°F
1	2.50	118	4.47	185	4.05	170	2.99	135
2	6.61	256	7.36	280	6.95	268	5.08	205
3	7.98	301	8.61	322	8.42	315	6.27	245
4	9.03	335	9.29	344	9.43	348	7.26	277
5	9.71	357	9.80	360	10.08	369	7.82	296
6	10.10	370	10.13	371	10.50	383	8.30	311
7	10.38	379	10.40	380	10.83	395	8.76	326
8								
9	10.92	397	11.02	400	11.48	415	9.66	355
10								
0	11.39	412	11.56	417	11.91	430	10.46	382
1m	6.88	265	7.44	283	7.09	272	4.95	201
2m	5.41	216	6.80	262	6.60	255	5.00	203
Gas Inlet Pressure (psi)	10		20		30		40	
Flow Rate (sec/0.1 ft^3)	49.6		26		17		11.53	
Furnace Temp. (°F)	410		430		420		400	
Gas Outlet Temp. (°C)	23		23.5		17		20.5	
Mass Flow (lb/in^2-sec) $\times 10^{-4}$	3.28		6.27		9.8		14.3	

Furnace Temperature = 600 °F

Nitrogen Gas

Thermocouple	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F
1	4.98	202	5.25	211	4.96	202	4.21	176	3.55	154
2	9.77	260	9.7	367	8.3	326	7.56	287	6.17	241
3	12.19	438	11.78	425	10.78	393	9.5	350	7.99	301
4	13.7	482	13.13	469	12.3	442	11.3	410	9.42	347
5	14.7	520	14.17	502	13.36	476	12.1	435	10.4	380
6	15.23	537	14.78	522.4	14.16	502	12.97	404	11.31	410
7	15.5	546	15.17	535	14.61	517	13.54	482	12.0	432
8										
9	16.4	575	16.18	568	15.64	550	14.73	521	13.4	477.5
10			16.5	579	15.95	560	15.32	540	14.18	503
0	16.65	583	16.83	590	16.35	574	15.91	560	14.79	525
1m	10.2	373	10.12	370	8.83	329	7.52	285	5.74	227
2m	7.35	280								
Gas Inlet Pressure (psi)	5		10		20		30		40	
Flow Rate (sec/0.1 ft^3)	111.6		69.1		32.5		19.5		13.1	
Furnace Temp. (°F)	590		600		596		600		590	
Gas Outlet Temp. (°C)	15		15.8		16.4		17.2		18.1	
Mass Flow (lb/in^2-sec) x 10^{-4}	1.5		2.42		5.14		8.55		12.08	

Furnace Temperature = 800°F

Nitrogen Gas

Thermocouple	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F
1	6.69	258	4.36	181	4.42	183	4.35	181
2	13.28	474	11.18	405	9.66	355	8.60	321
3	16.3	572	14.3	507	12.8	458	11.57	418
4	18.3	637	16.7	585	15.13	534	13.6	484
5	19.5	676	18.3	637	16.8	588	15.08	532
6	21.15	697	19.25	668	18.1	630	16.4	575
7	20.5	709	19.9	690	18.9	660	17.5	611
8								
9	21.9	755	21.4	738	20.75	717	19.5	677
10	22.4	770	22.1	760	21.6	745	20.5	709
0	23.0	790	22.8	784	22.5	774	21.6	745
1m	13.7	487	11.68	422	10.1	370	8.71	325
2m								
Gas Inlet Pressure (psi)	10		20		30		40	
Flow Rate (Sec/0.1 ft^2)	84.5		40.8		24.1		16.1	
Furnace Temp. (°F)	810		800		810		800	
Gas Outlet Temp. (°C)	20.6		21.3		21.8		22.3	
Mass Flow (lb/in^2-sec) x 10^{-4}	1.95		4.02		6.8		10.2	

Furnace Temperature = 1000°F

Nitrogen Gas

Thermocouple	Millivolts	°F	Millivolts	°F	Millivolts	°F	Millivolts	°F	Millivolts	°F
1	12.09	435	9.11	338	9.03	335	8.09	305	7.04	270
2	19.0	660	16.3	572	15.0	530	13.91	494	12.53	450
3	22.0	760	20.2	700	18.3	637	16.7	585	15.75	555
4	24.2	830	22.2	780	21.1	728	19.5	676	18.5	644
5	25.5	870	24.2	829	22.8	784	21.4	738	20.3	702
6	26.3	896	25.3	865	24.1	825	22.9	787	22.0	757.5
7	26.8	912.5	26.1	890	25.1	858	23.95	820	23.3	800
8										
9	28.0	951	27.5	935	26.9	915	26.05	887	25.55	872
10	28.6	970	28.3	960	27.7	941	26.9	915	26.6	906
0	29.2	989	28.9	980	28.5	967	27.8	945	27.5	935
1m	19.9	690	17.3	605	16.0	562	14.21	504	12.79	458

Gas Inlet Pressure (psi)	10	20	30	40	50
Flow Rate (sec/0.1 ft^3)	115.4	56.6	34.8	22.6	16.1
Furnace Temp. (°F)	1000°	1000	1000	1000	1000
Gas Outlet Temp. (°C)	23	23	23	23	23
Mass Flow (lb/in^2-sec) x 10^{-4}	1.412	2.88	4.69	7.22	10.13

Furnace Temperature = 70°F

Hydrogen Gas

Gas Inlet Pressure (psi)	Flow Rate (sec/1.0 ft^3)	Mass Flow (lb/in^2-sec) x 10^{-5}
10	137	8.06
20	68.2	16.2
30	43.4	25.4
40	31	35.6
50	23.9	46.2
60	19.8	55.8

Furnace Temperature = 400°F

Hydrogen Gas

Thermocouple	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F
1	3.70	160	2.73	126	1.62	88	1.1	70
2	6.2	245	5.27	212	4.08	172	3.48	151
3	7.12	273	5.89	232	4.91	200	4.59	189
4	8.1	305	6.58	255	5.68	225	4.77	195
5	8.68	324	7.03	270	6.09	238	5.1	206
6	9.14	339	7.5	285	6.54	253	5.4	210
7	9.47	350	7.91	298	6.86	264	5.85	231
8								
9	10.24	375	8.88	330	7.91	298	6.96	262
10	10.58	386	9.3	345	8.41	315	7.45	284
0	10.8	393	9.65	355	8.91	331	7.85	297
1M	6.53	254	5.16	209	3.85	164	3.0	135
2M								
Gas Inlet Pressure (psi)	10		20		30		40	
Flow Rate (Sec/1.0 ft^3)	261.7		120		70		47	
Furnace Temp. (°F)	390		390		400		410	
Gas Outlet Temp. (°C)	19		19		19		20	
Mass Flow (lb/in^2-sec) x 10^{-5}	4.55		9.91		17.0		25.2	

Furnace Temperature = 600

Hydrogen Gas

Thermocouple	Milli-volt	°F	Milli-volt	°F	Milli-volt	°F	Milli-volt	°F
1	5.97	235	3.34	148	1.81	95	1.1	70
2	10.28	376	8.57	320	6.06	238	4.12	173
3	11.73	418	10.02	367	7.43	283	5.62	223
4	13.2	471	11.68	423	9.1	337	6.69	258
5	14.03	499	12.73	455	10.11	370	7.45	283
6	14.6	517	13.64	485	11.08	402	8.2	308
7	15.1	533	14.3	507	12.01	432	9.12	338
8								
9	16.16	568	15.68	552	13.76	490	11.1	403
10	16.5	579	16.3	572	14.52	514	12.03	434
0	16.9	592	16.9	592	15.11	533	12.7	455
1m	10.62	392	8.61	321	5.92	234	3.95	167
Gas Inlet Pressure (psi)	10		20		30		40	
Flow Rate (sec/1 ft^3)	360		175		100		60	
Furnace Temp. (°F)	600		610		600		585	
Gas Outlet Temp. (°C)	22		23		23		23	
Mass Flow (lb/in^2-sec) x 10^{-5}	3.27		6.93		11.76		19.58	

8083

Furnace Temperature = 800°F

Hydrogen Gas

Thermocouple	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F
1	10.69	389	5.7	225	3.13	140	1.89	98
2	15.79	555	12.46	447	10.23	375	7.07	270
3	17.5	611	15.47	545	12.11	435	9.71	357
4	19.2	666	17.2	602	14.6	517	11.8	393
5	20.10	692	18.5	645	16.1	565	13.19	470
6	20.6	712	19.3	670	17.5	610	14.49	513
7	21.1	728	19.95	690	18.5	645	15.75	555
8								
9	22.25	765	21.5	741	20.5	709	18.45	642
10	22.8	784	22.1	760	21.3	735	19.55	678
0	23.2	796	22.65	778	21.9	755	20.4	705
1M	16.3	572	13.28	475	10.11	370	7.2	275
2M								
Gas Inlet Pressure (psi)	10		20		30		40	
Flow Rate (sec/1.0 ft^3)	462		224		123		77	
Furnace Temp. (°F)	820		820		820		810	
Gas Outlet Temp. (°C)	24		24		24.5		24.5	
Mass Flow (lb/in^2-sec) x 10^{-5}	2.53		5.55		9.46		15.16	

Furnace Temperature = 1000

Hydrogen Gas

Thermocouple	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F	Milli-volts	°F
1	13.4	477.5	9.12	339	5.11	206	2.9	132
2	18.7	650	19.4	673	15.45	545	10.53	385
3	20.8	719	21.8	750	18.5	645	14.63	518
4	22.1	760	23.7	813	21.2	731	17.3	605
5	23.1	794	24.6	841	22.7	780	18.9	657
6	23.7	813	25.3	865	23.0	820	20.4	705
7	24.3	832	25.9	884	24.8	849	21.7	748
8								
9	26.25	895	27.2	925	26.6	906	24.2	829
10	27.1	921	27.85	945	27.2	925	25.25	863
0	27.9	949	28.4	694	27.95	950	26.2	893
1m	19.3	670	19.7	683	15.58	549	11.14	405
Gas Inlet Pressure (psi)	10		20		30		40	
Flow Rate (sec/1 ft^3)	494.6		264		153		91.5	
Furnace Temp. (°F)	1010		1000		1000		990	
Gas Outlet Temp. (°C)	26		25		25		25	
Mass Flow (lb/in^2-sec) . 10^{-5}	2.36		4.42		7.59		12.72	

Furnace Temperature = 1000°F

Hydrogen Gas

Thermocouple	Millivolts	°F	Millivolts	°F	Millivolts	°F
1	1.89	97.5	1.72	94	1.67	90
2	6.34	247*	5.49	219	4.38	181
3	11.34	410	11.61	420	7.52	285
4	12.52	449	12.55	450	7.4	282
5	14.07	500	14.05	500	8.14	306
6	15.45	545	15.47	545	8.87	330
7	16.85	590	17.0	595	9.84	361
8						
9	19.9	690	20.15	697	13.52	481
10	21.5	741	21.6	745	14.32	507
0	22.65	779	22.75	782	19.35	671
1M	6.82	262	6.56	255	4.03	170
2M						
Gas Inlet Pressure (psi)	50		60		70	
Flow Rate (sec/1.0 ft^3)	57		45		27	
Furnace Temp. (°F)	985		1000		980	
Gas Outlet Temp. (°C)	25.5		26.5		27.5	
Mass Flow (lbs/in^2-sec) $\times 10^{-5}$	20.4		25.8		42.9	

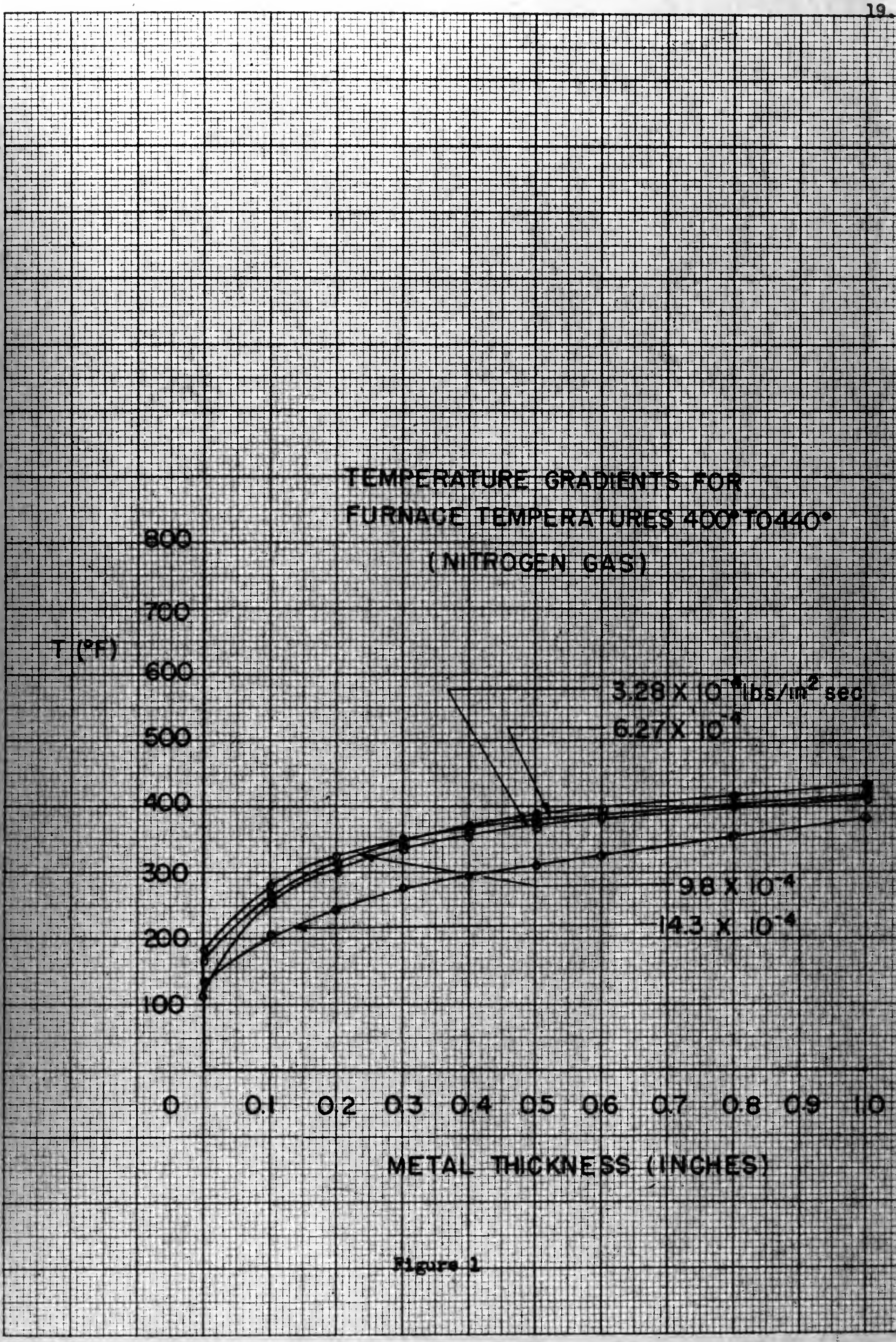

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURES 400° TO 440°
(NITROGEN GAS)
T (°F)
800
700
600
500
400
300
200
100
3.28 X 10⁻⁴ lbs/in² sec
6.27 X 10⁻⁴
9.8 X 10⁻⁴
14.3 X 10⁻⁴
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 1

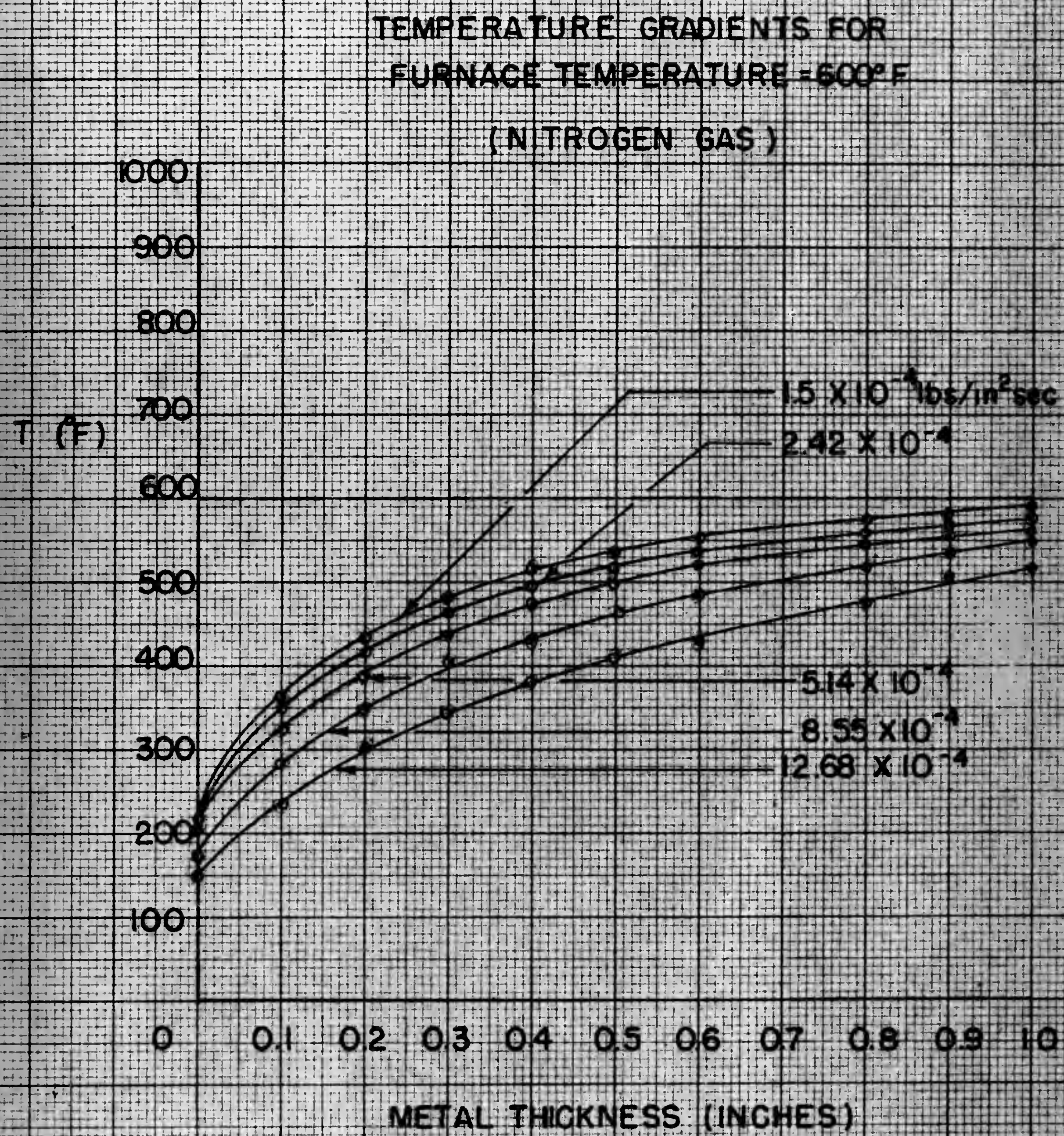

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE = 600° F
(NITROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
1.5 X 10⁻⁴ lbs/in² sec
2.42 X 10⁻⁴
5.14 X 10⁻⁴
8.55 X 10⁻⁴
12.68 X 10⁻⁴
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 2

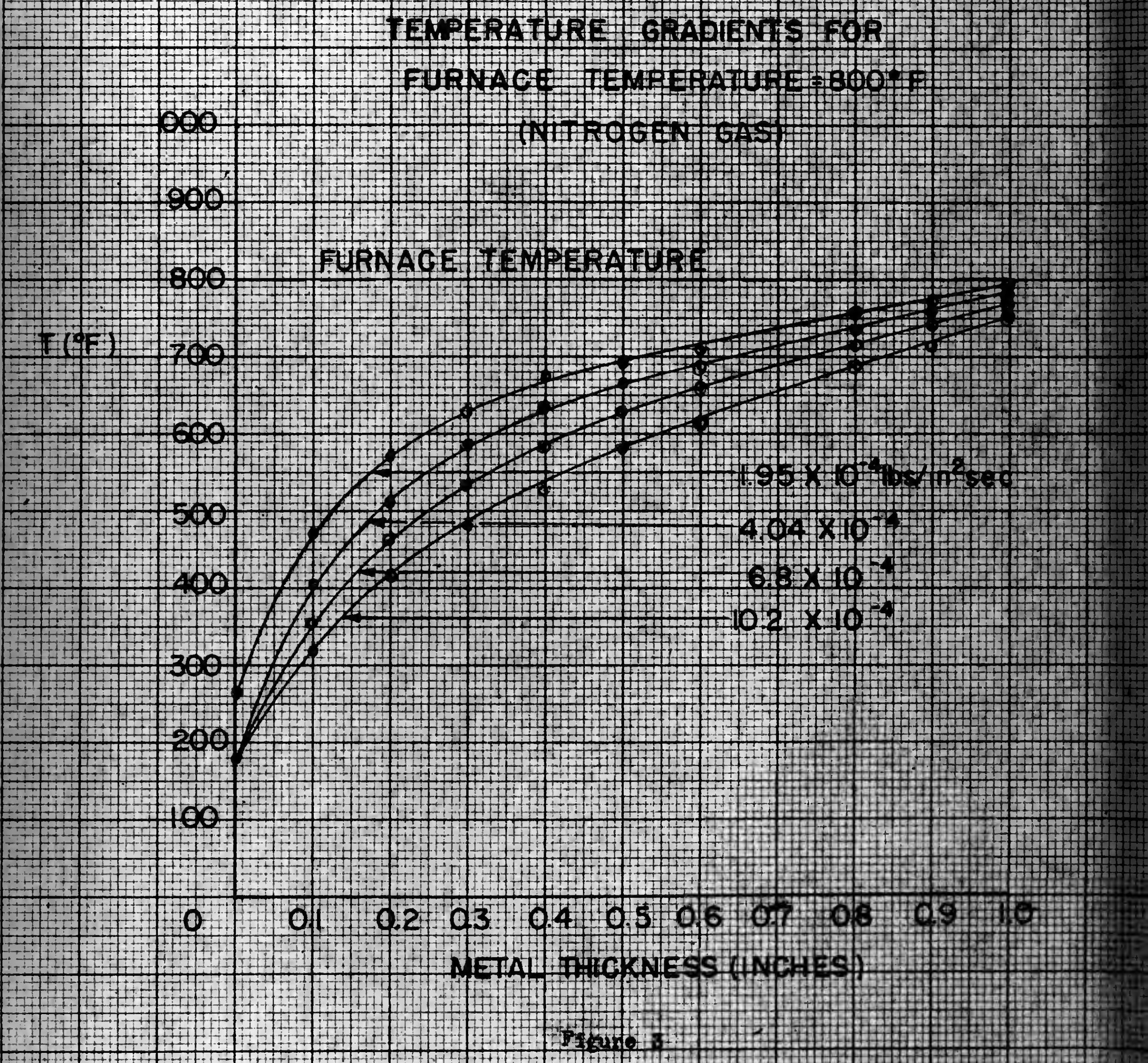

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE = 800° F
(NITROGEN GAS)
FURNACE TEMPERATURE
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.95 X 10⁻⁴ lbs/in² sec
4.04 X 10⁻⁴
6.8 X 10⁻⁴
10.2 X 10⁻⁴
METAL THICKNESS (INCHES)

Figure 3

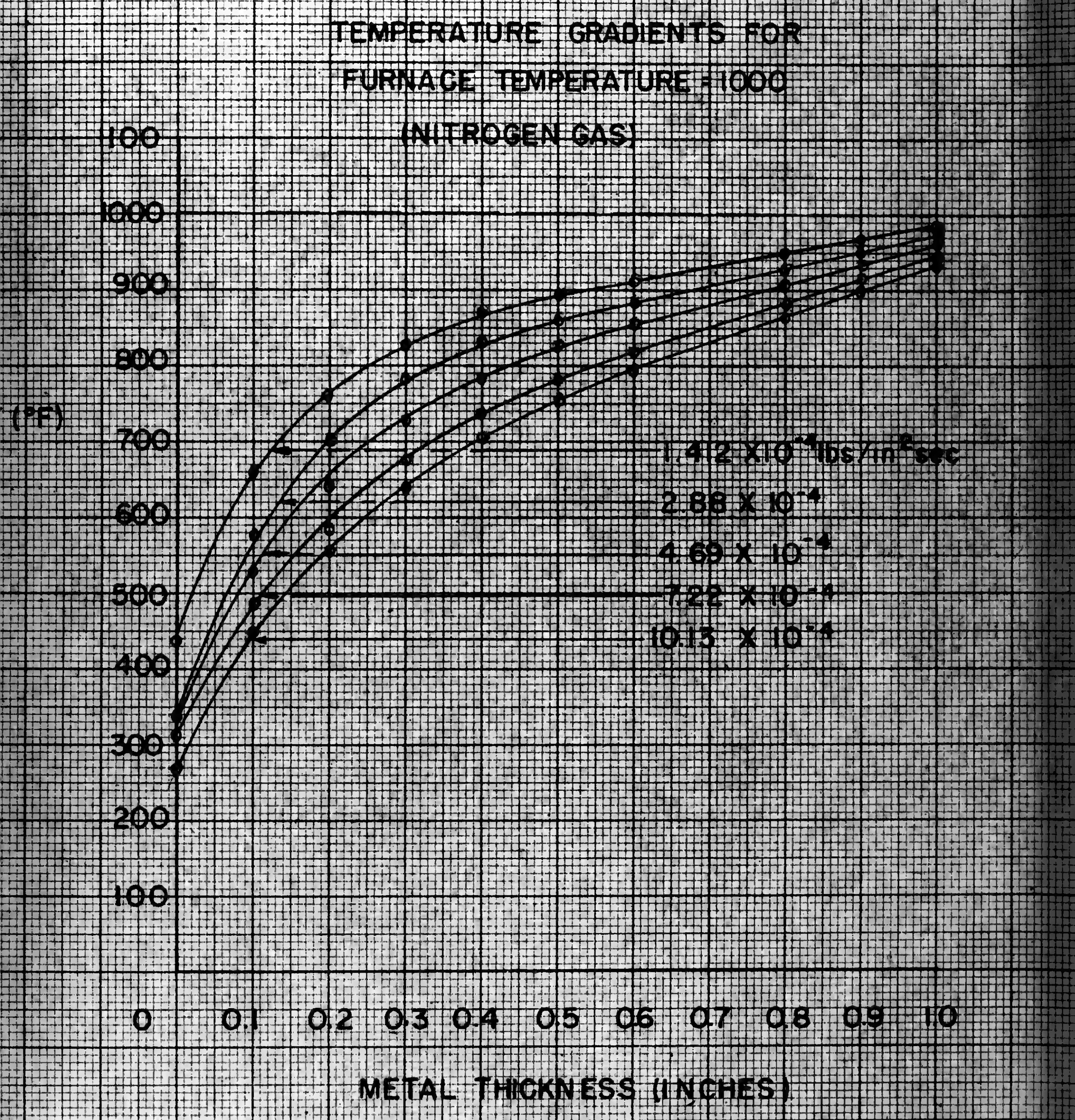
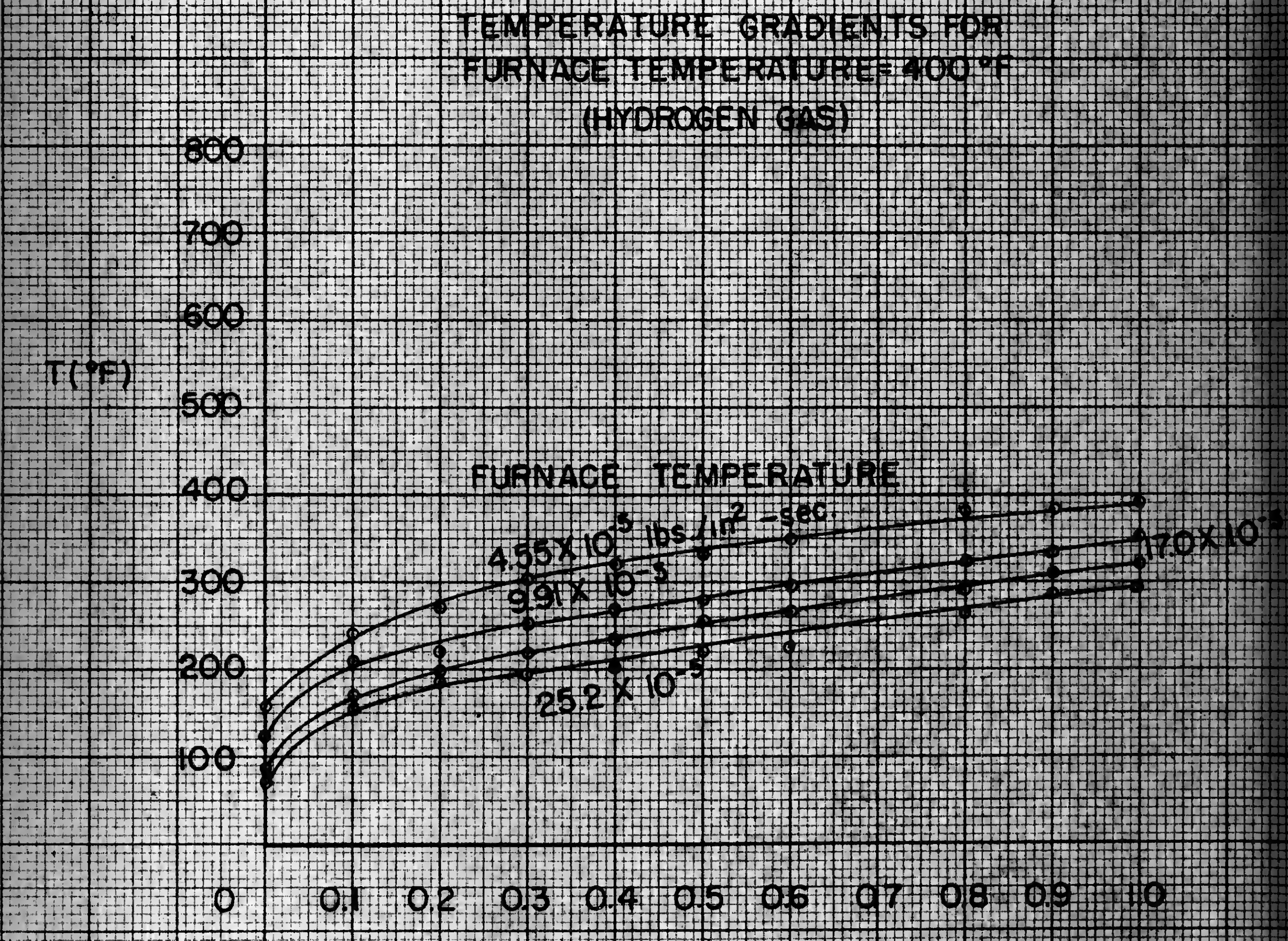

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE = 1000
(NITROGEN GAS)
100
1000
900
800
(°F)
700
600
500
400
300
200
100
1.42 X 10⁻⁴ lbs/in² sec
2.88 X 10⁻⁴
4.69 X 10⁻⁴
7.22 X 10⁻⁴
10.13 X 10⁻⁴
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 4



TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE = 400 °F
(HYDROGEN GAS)
T(°F)
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
FURNACE TEMPERATURE
4.55 X 10^-5 lbs./in^2 -sec.
9.91 X 10^-5
17.0 X 10^-5
25.2 X 10^-5
METAL THICKNESS (INCHES)

Figure 5

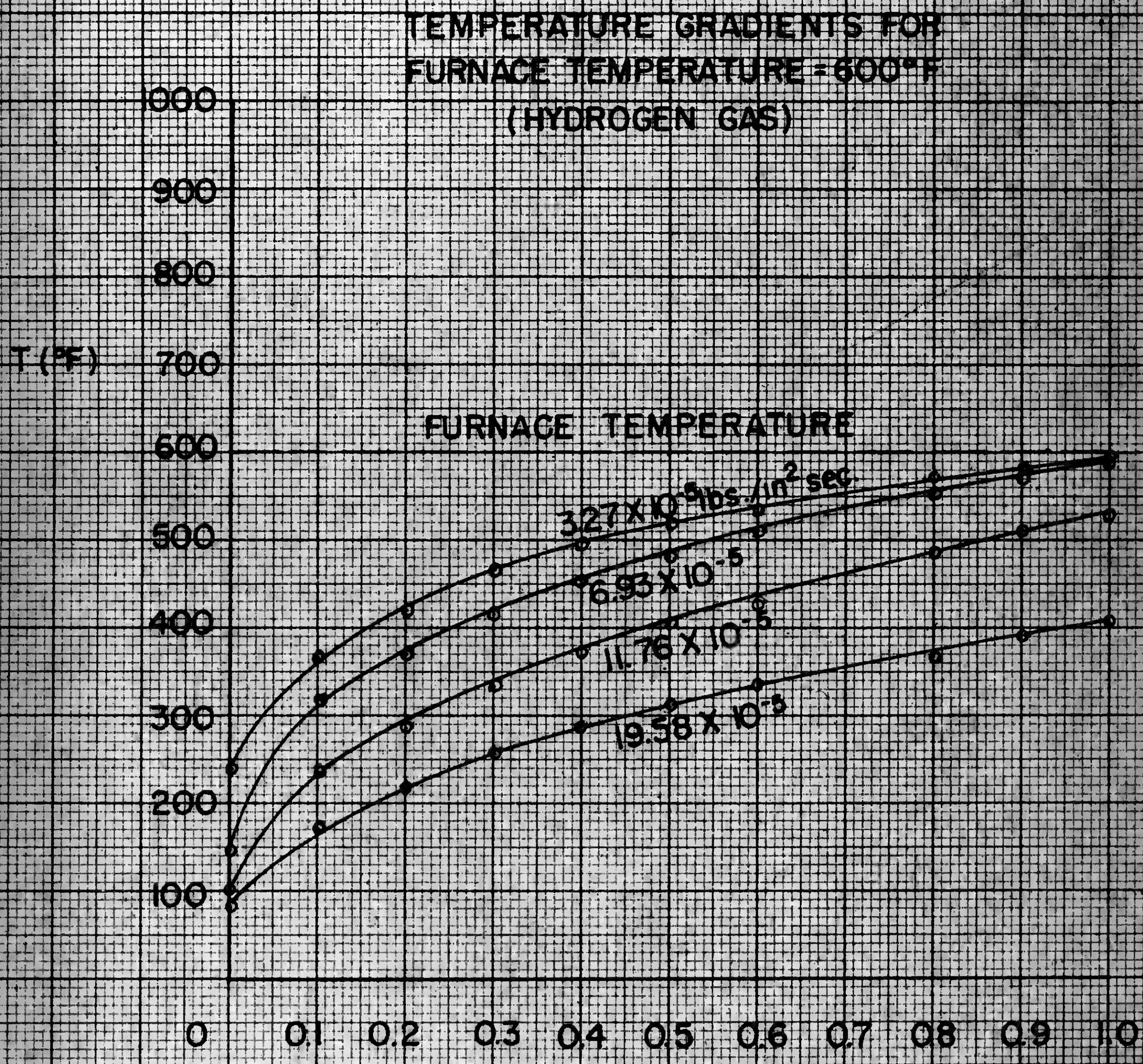

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE = 600°F
(HYDROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
FURNACE TEMPERATURE
3.27 X 10-5 lbs./in2 sec
6.93 X 10-5
11.76 X 10-5
19.58 X 10-5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 6

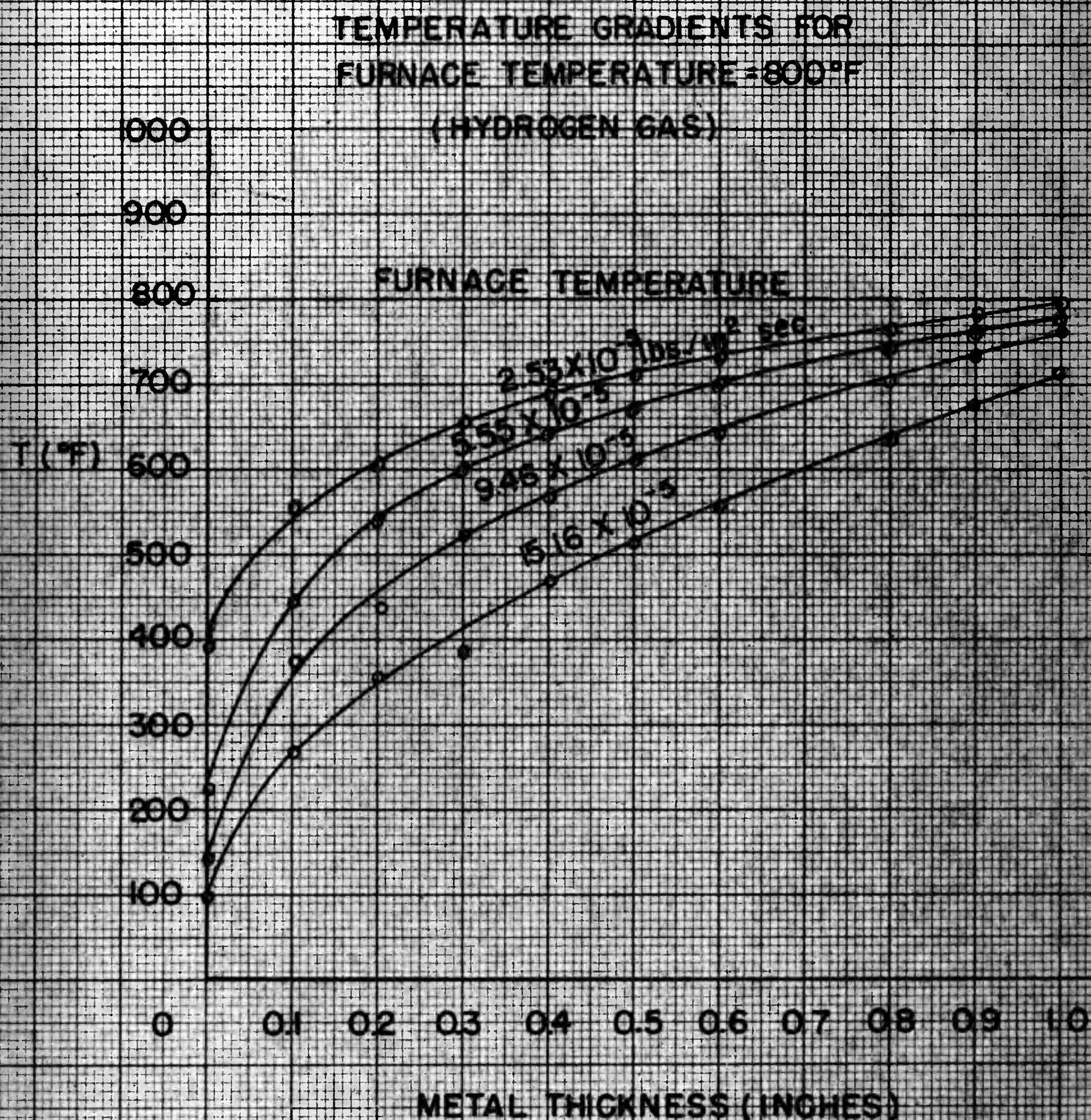

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE = 800°F
(HYDROGEN GAS)
FURNACE TEMPERATURE
2.53 X 10^-5 lbs/ft^2 sec
5.55 X 10^-5
9.46 X 10^-5
15.16 X 10^-5
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 7

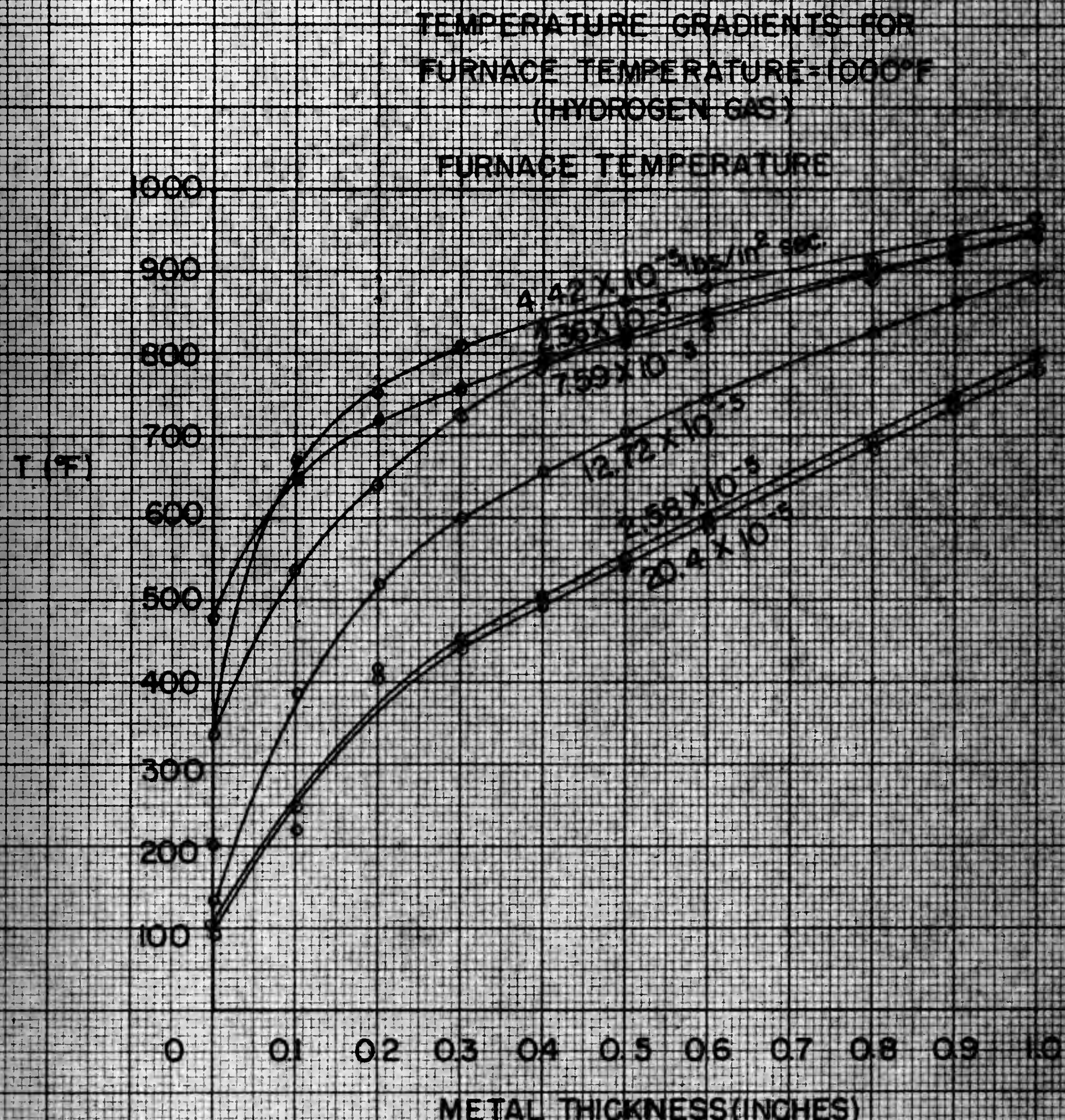

TEMPERATURE GRADIENTS FOR
FURNACE TEMPERATURE=1000°F
(HYDROGEN GAS)
FURNACE TEMPERATURE
4.42 X 10^-5 lbs/in^2 sec.
5.36 X 10^-5
7.59 X 10^-5
12.72 X 10^-5
2.58 X 10^-5
20.4 X 10^-5
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS(INCHES)

Figure 8

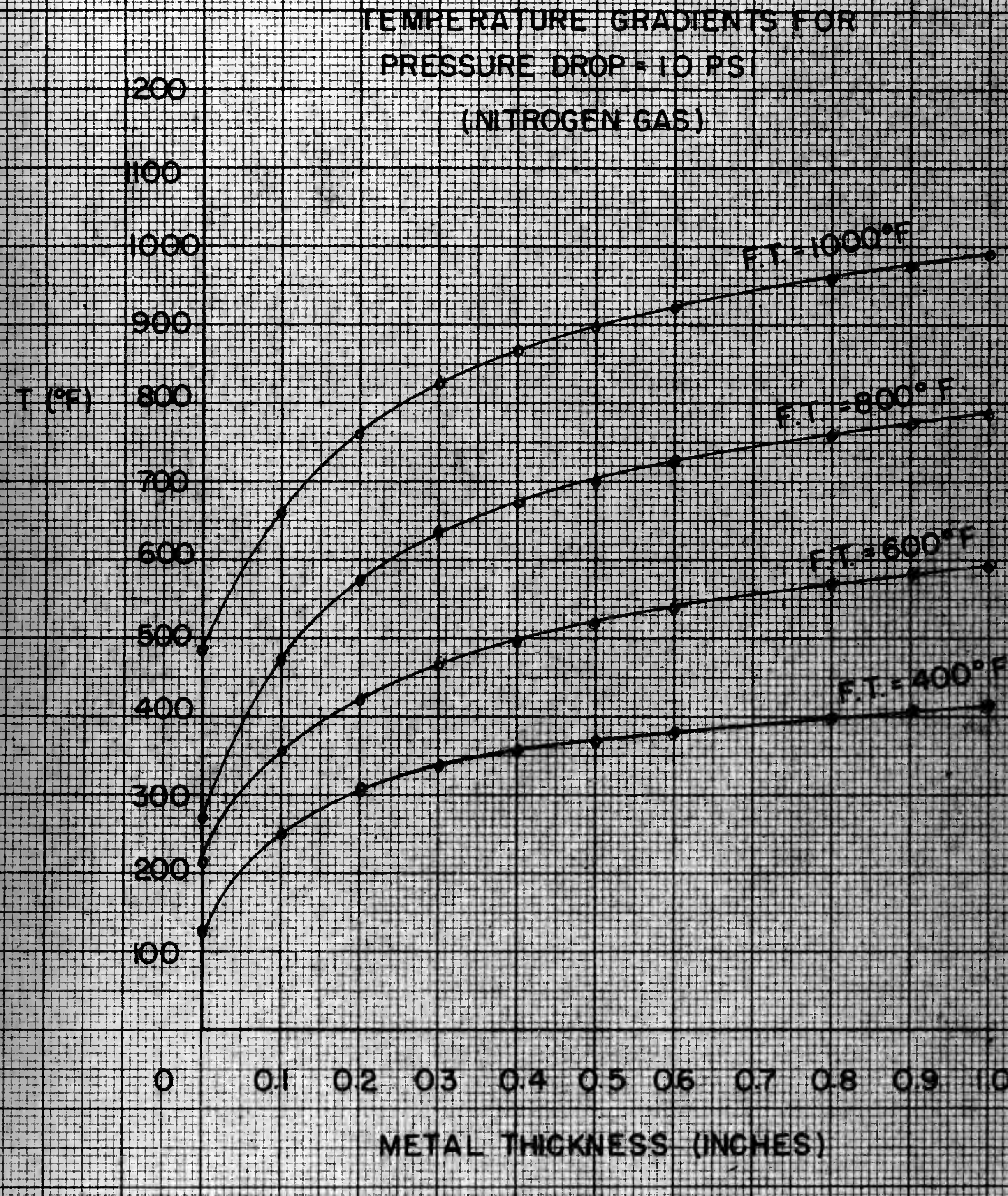

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 1.0 PSI
(NITROGEN GAS)
T (°F)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
F.T. = 1000°F
F.T. = 800° F
F.T. = 600°F
F.T. = 400°F
METAL THICKNESS (INCHES)

Figure 9

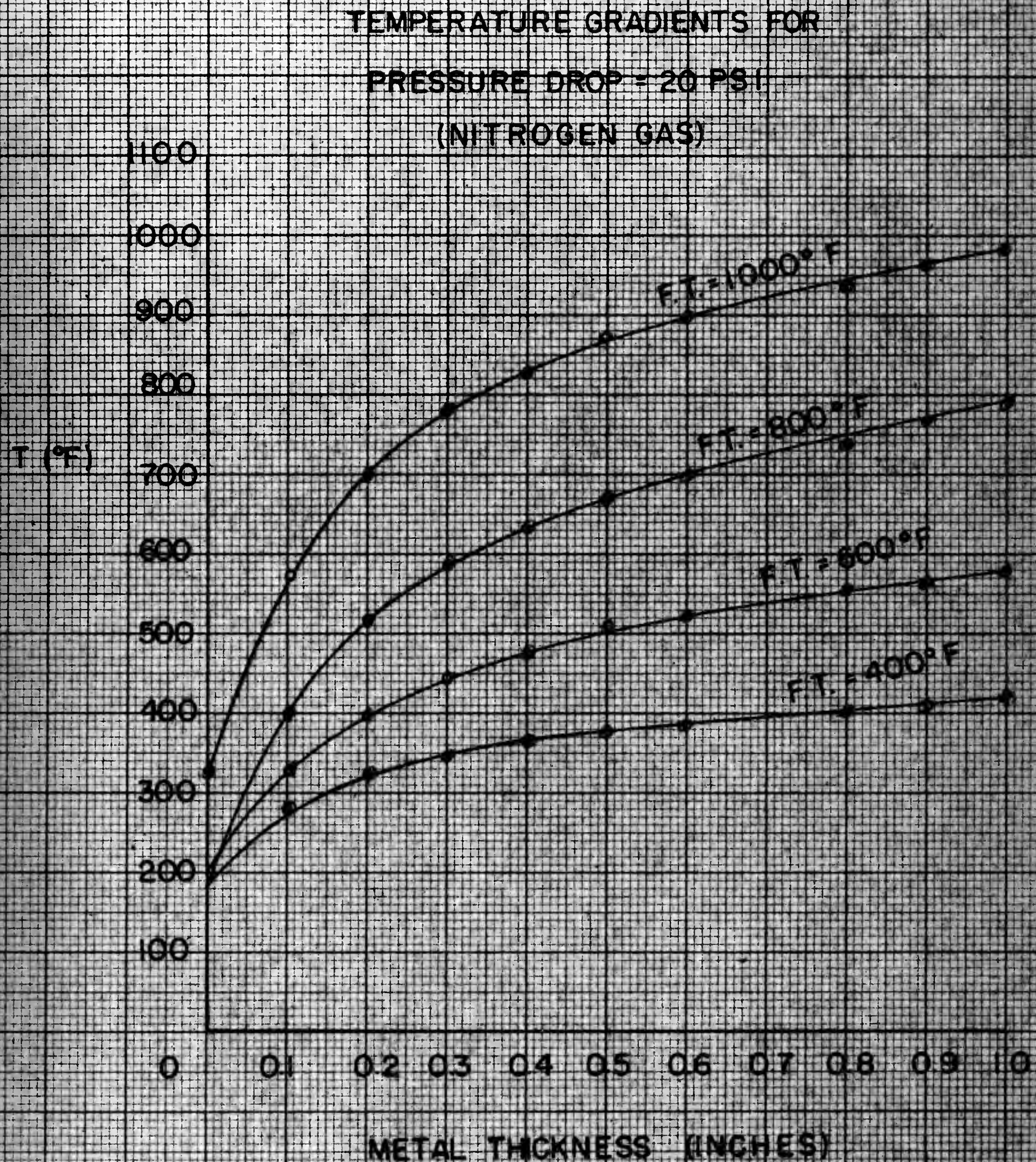

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 20 PSI
(NITROGEN GAS)
T (°F)
1100
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
F.T. = 1000° F
F.T. = 800° F
F.T. = 600° F
F.T. = 400° F
METAL THICKNESS (INCHES)

Figure 10

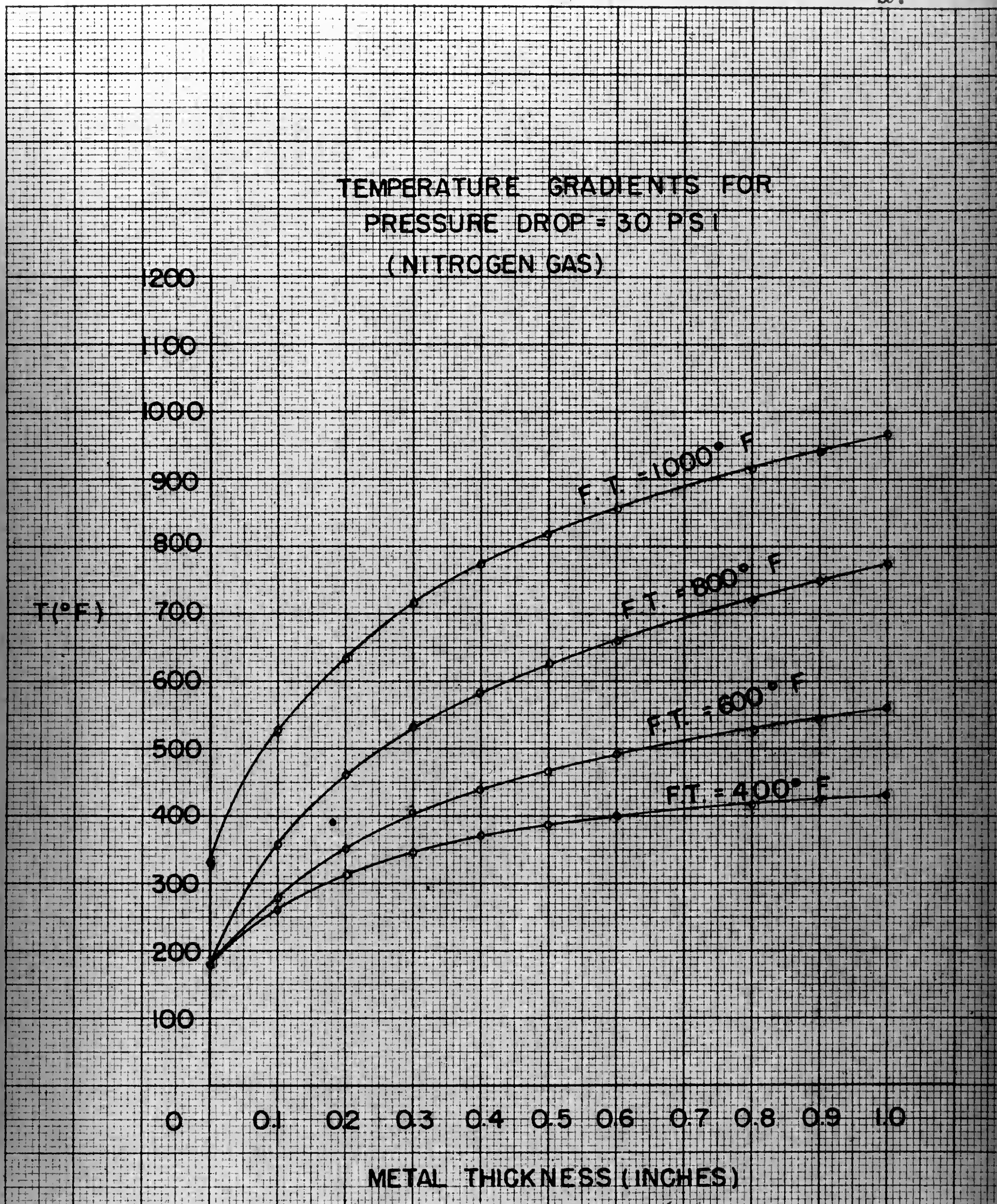

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 30 PSI
(NITROGEN GAS)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
T(°F)
F.T. =1000° F
F.T. =800° F
F.T. =600° F
F.T. =400° F
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 11

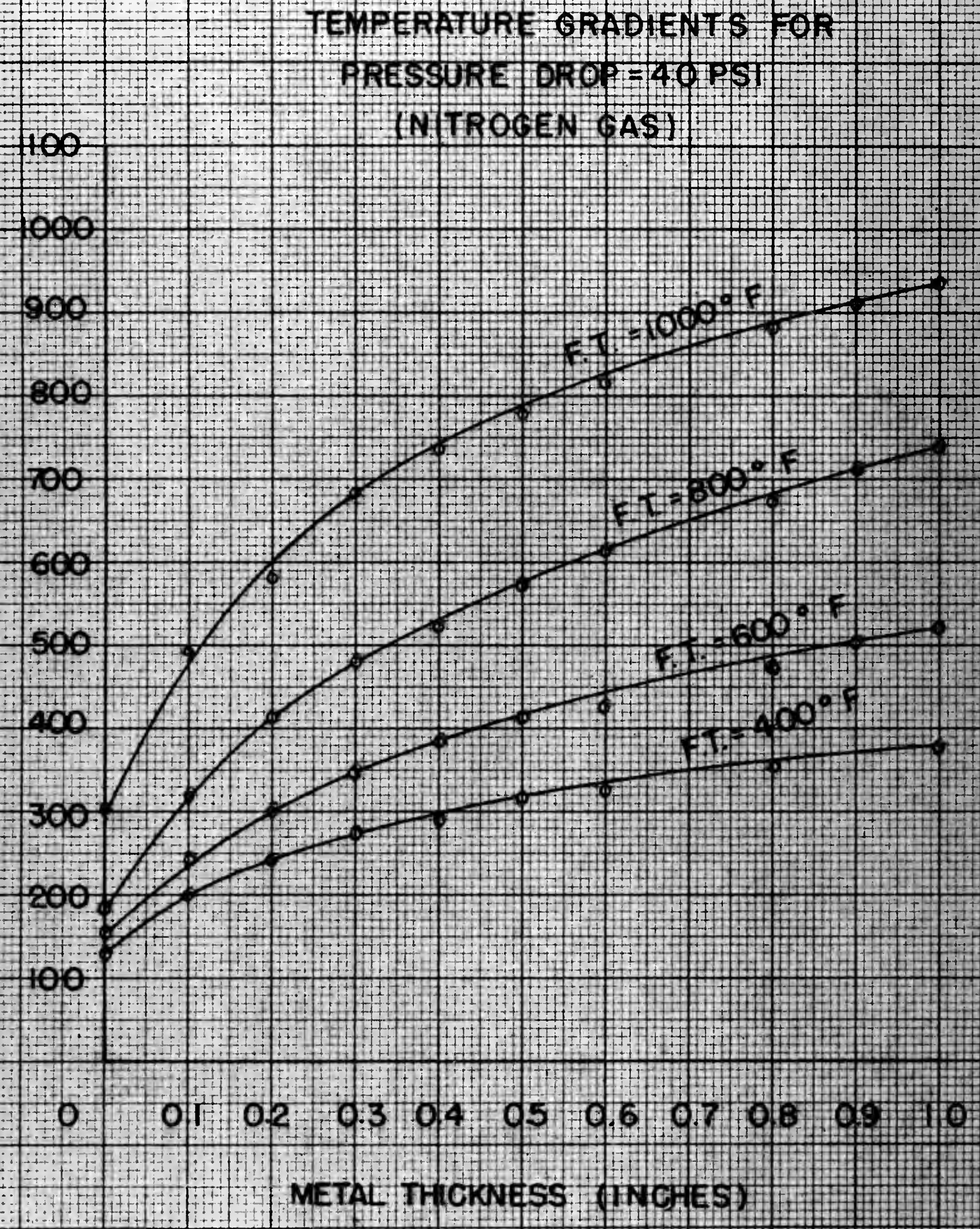
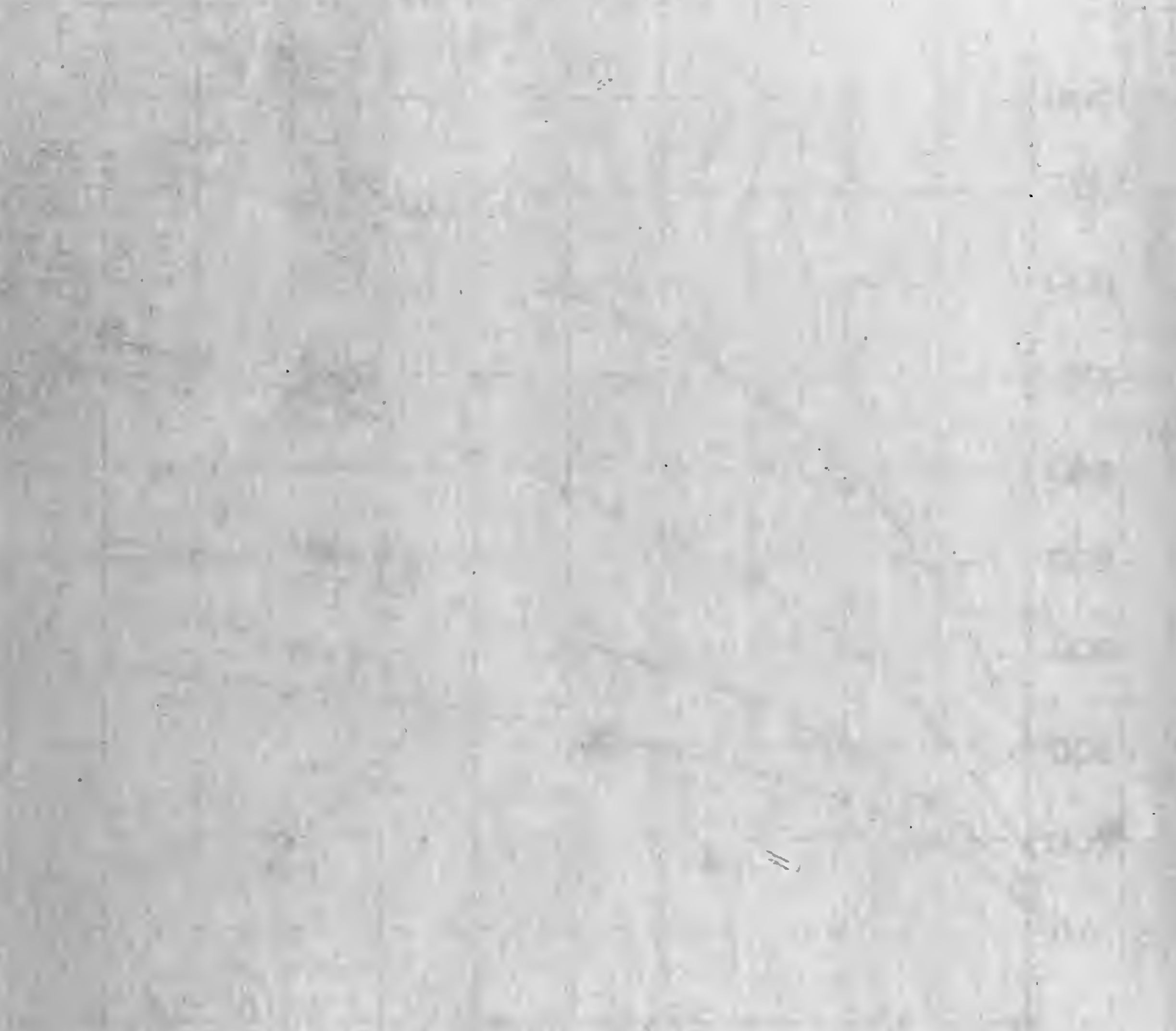

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 40 PSI
(NITROGEN GAS)
1100
1000
900
800
700
600
500
400
300
200
100
T (°F)
F.T. = 1000° F
F.T. = 800° F
F.T. = 600° F
F.T. = 400° F
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)

Figure 12



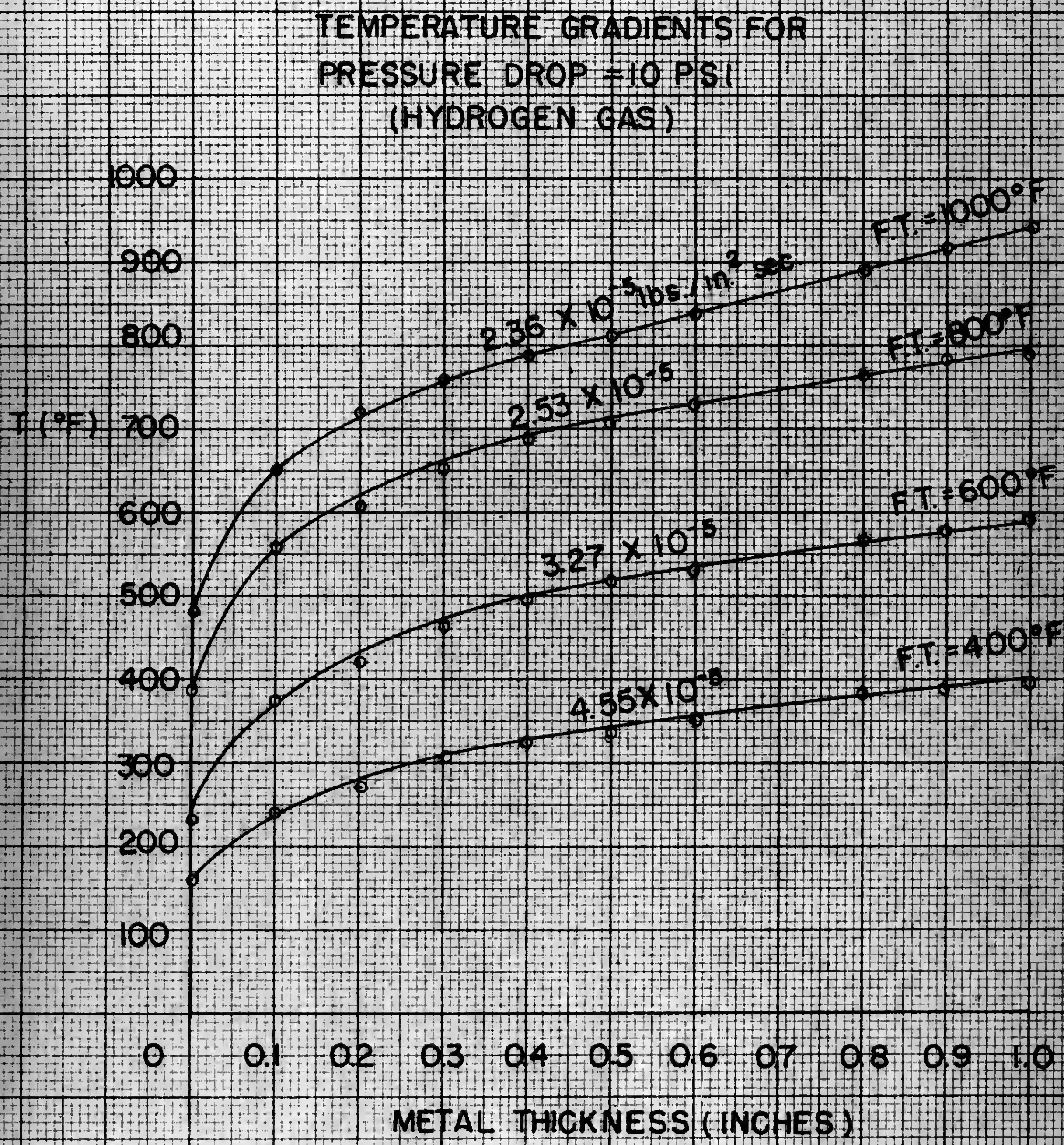

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 10 PSI
(HYDROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)
F.T. = 1000°F
2.36 X 10^-5 lbs./in.^2 sec
F.T. = 800°F
2.53 X 10^-5
F.T. = 600°F
3.27 X 10^-5
F.T. = 400°F
4.55 X 10^-5

Figure 13

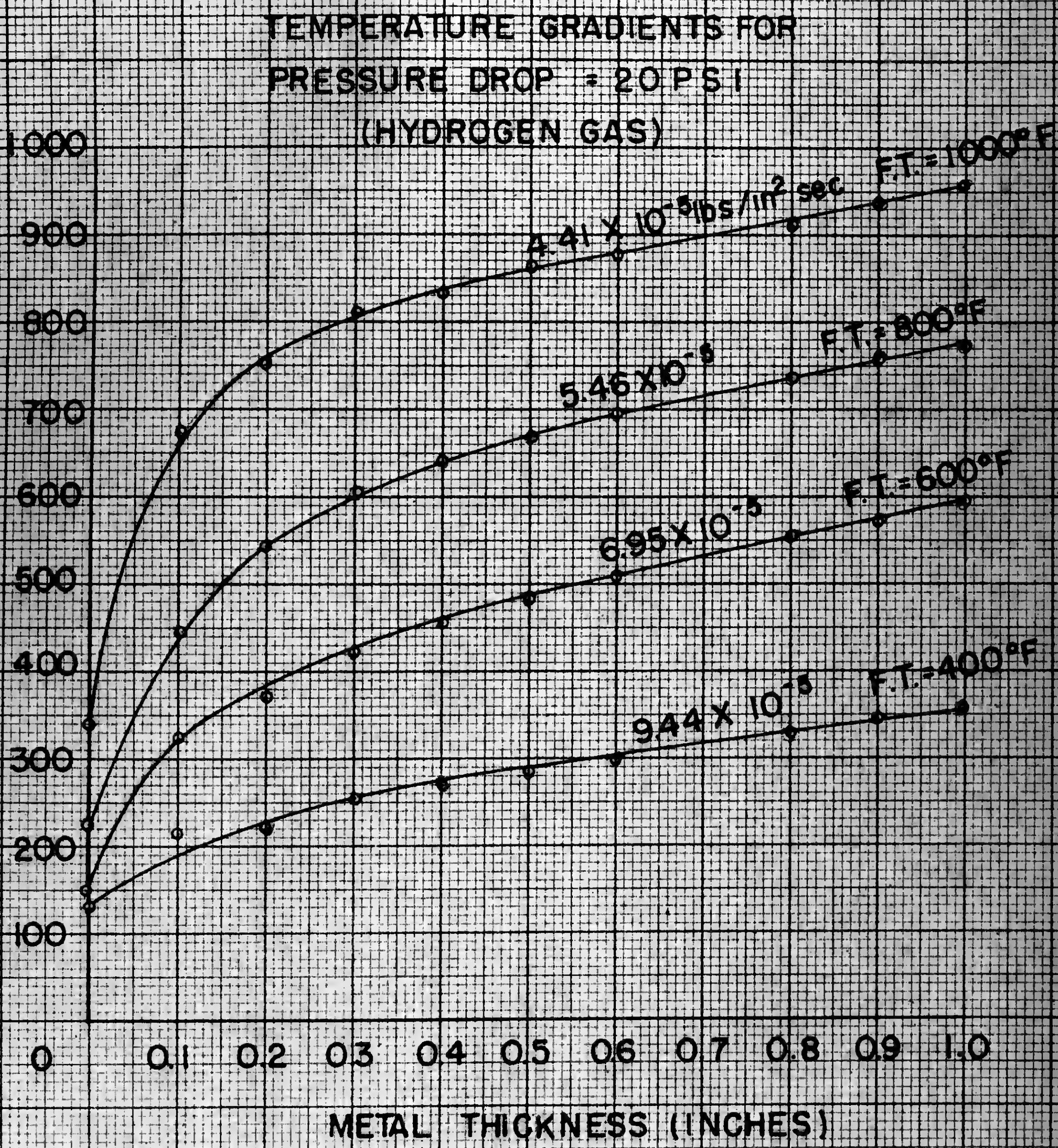

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 20 P S I
(HYDROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)
F.T.=1000°F
4.41 X 10^-5 lbs/in^2 sec
F.T.=800°F
5.46 X 10^-5
F.T.=600°F
6.95 X 10^-5
F.T.=400°F
9.44 X 10^-5

Figure 14

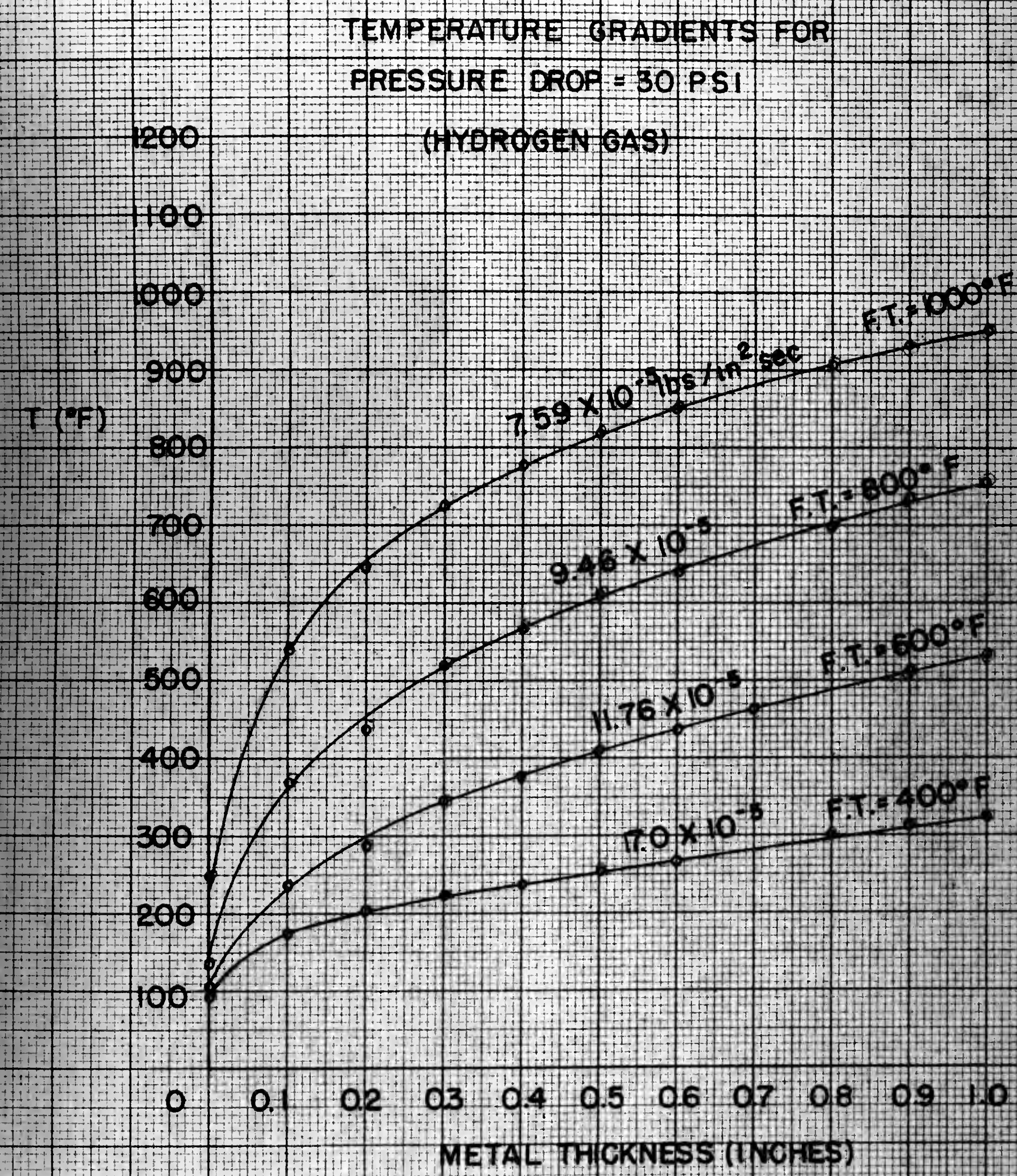

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 30 PSI
(HYDROGEN GAS)
T (°F)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)
F.T. = 1000° F
7.59 X 10^-5 lbs/in^2 sec
F.T. = 800° F
9.46 X 10^-5
F.T. = 600° F
11.76 X 10^-5
F.T. = 400° F
17.0 X 10^-5

Figure 15

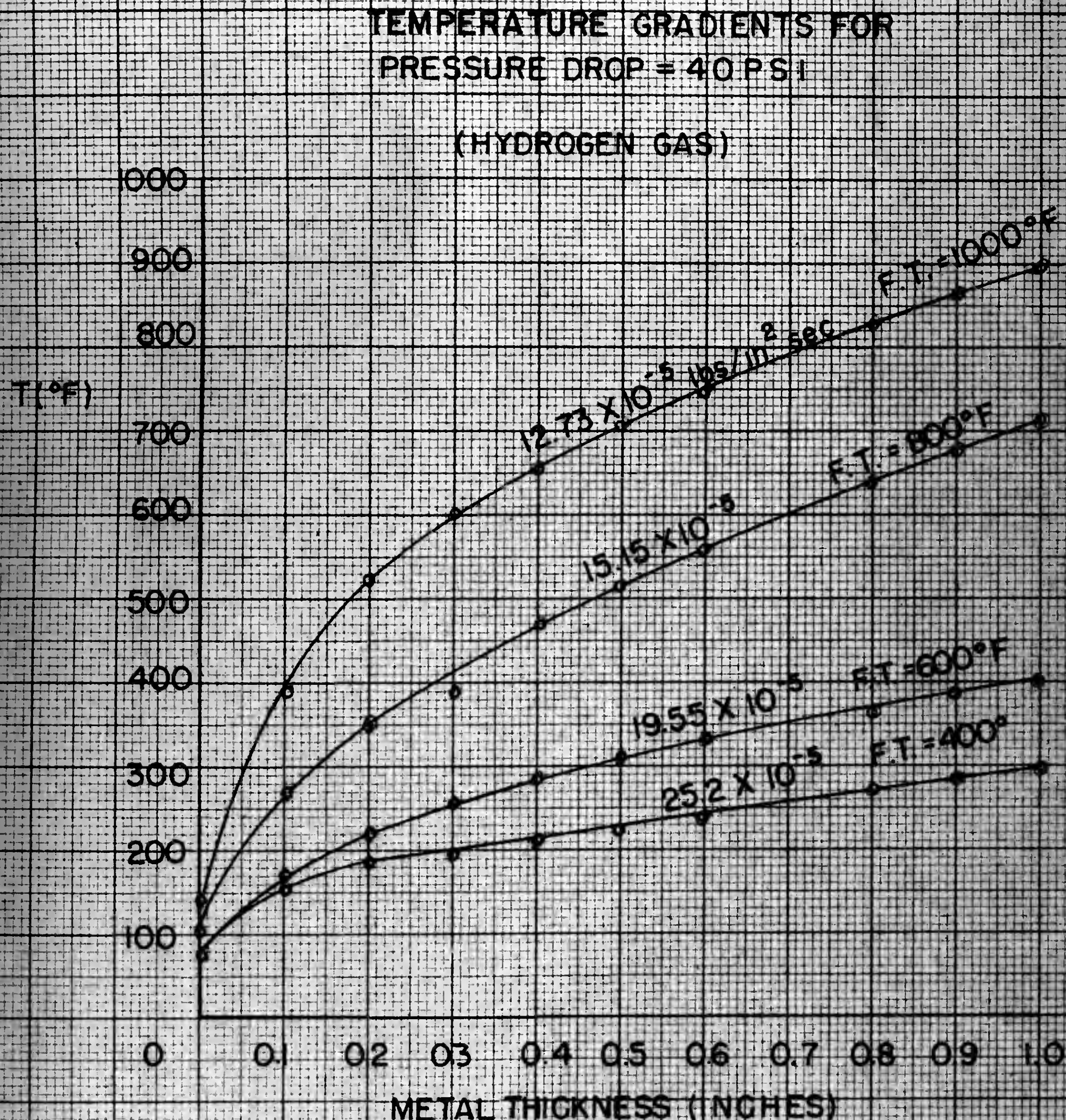
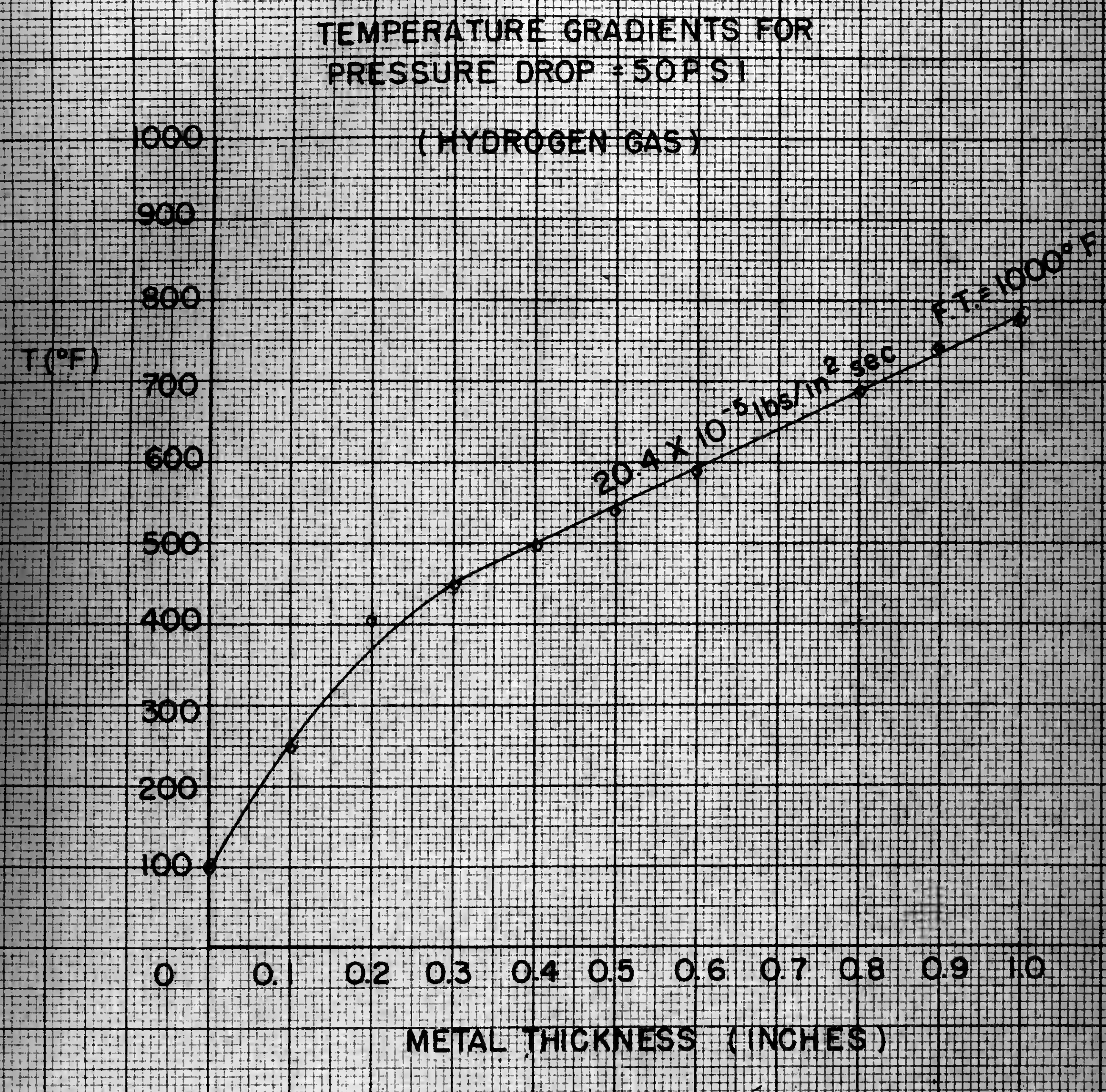

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 40 PSI
(HYDROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)
12.73 X 10^-5 lbs/in^2 sec
F.T. = 1000°F
15.15 X 10^-5
F.T. = 800°F
19.55 X 10^-5
F.T. = 600°F
25.2 X 10^-5
F.T. = 400°

Figure 16



TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 50 P S I
(HYDROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)
20.4 X 10⁻⁵ lbs/in² sec
F.T. = 1000° F

Figure 17

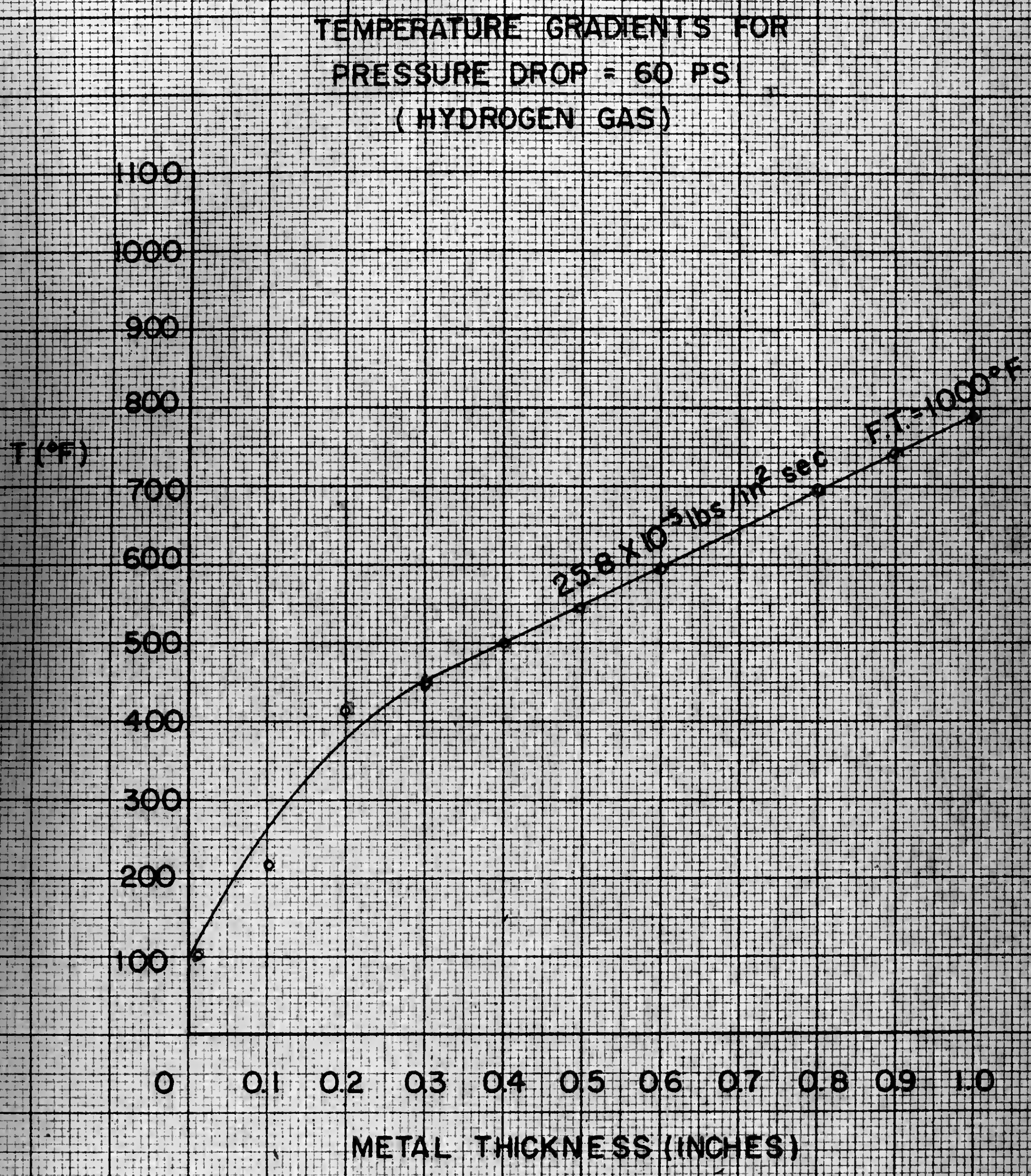

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 60 PSI
(HYDROGEN GAS)
T (°F)
1100
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
METAL THICKNESS (INCHES)
25.8 X 10⁻⁵ lbs/in² sec
F.T.=1000°F

Figure 18

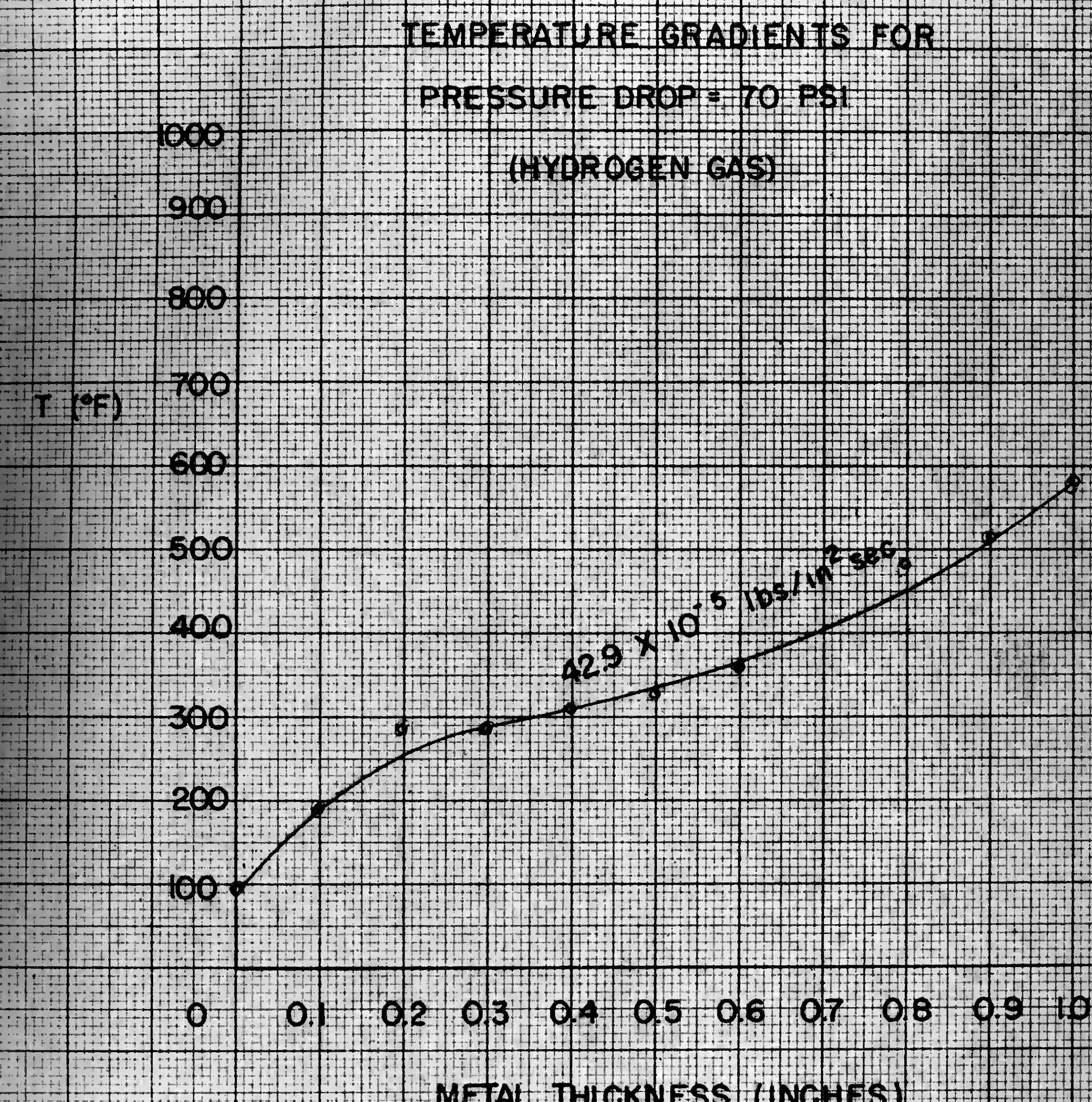
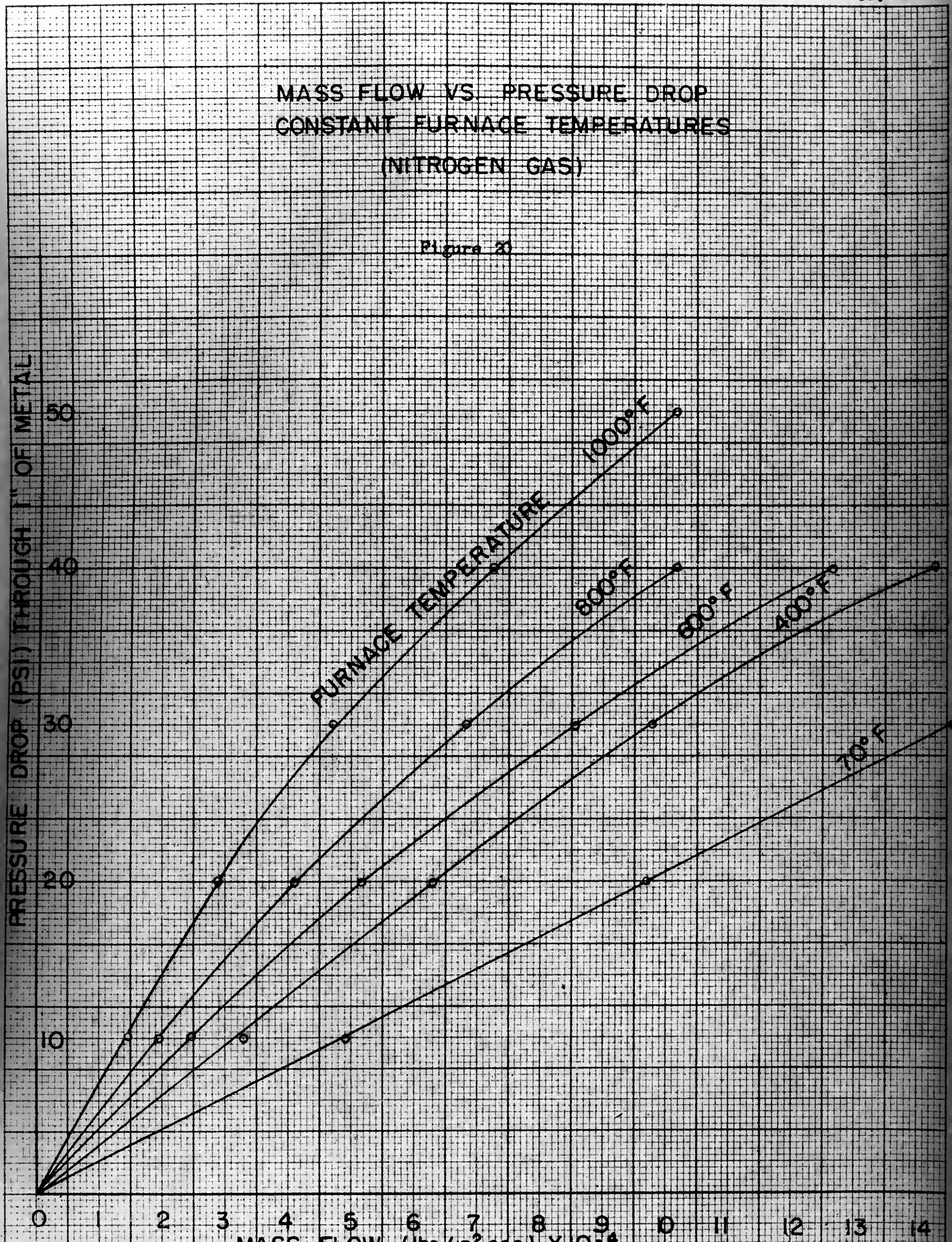
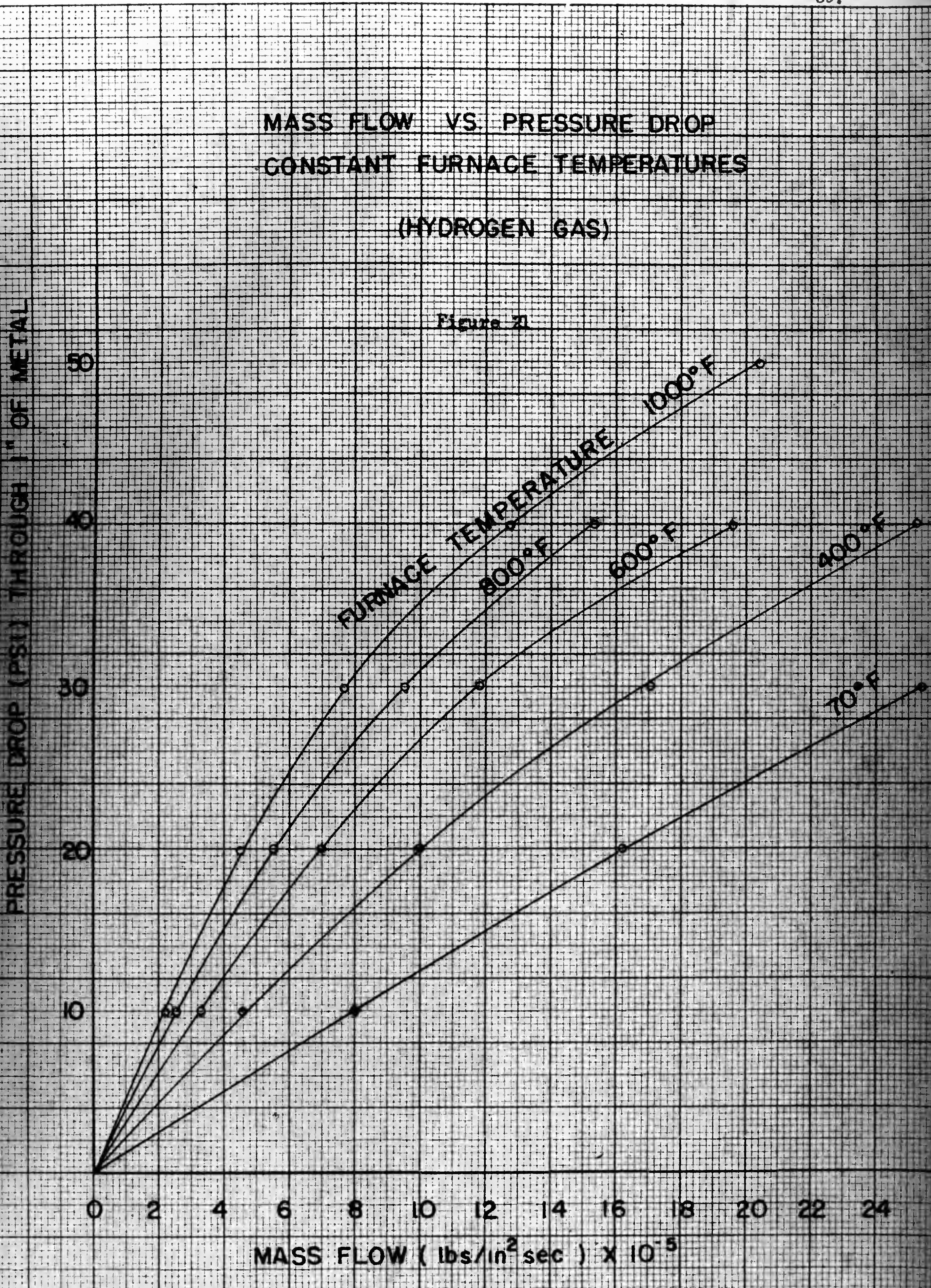
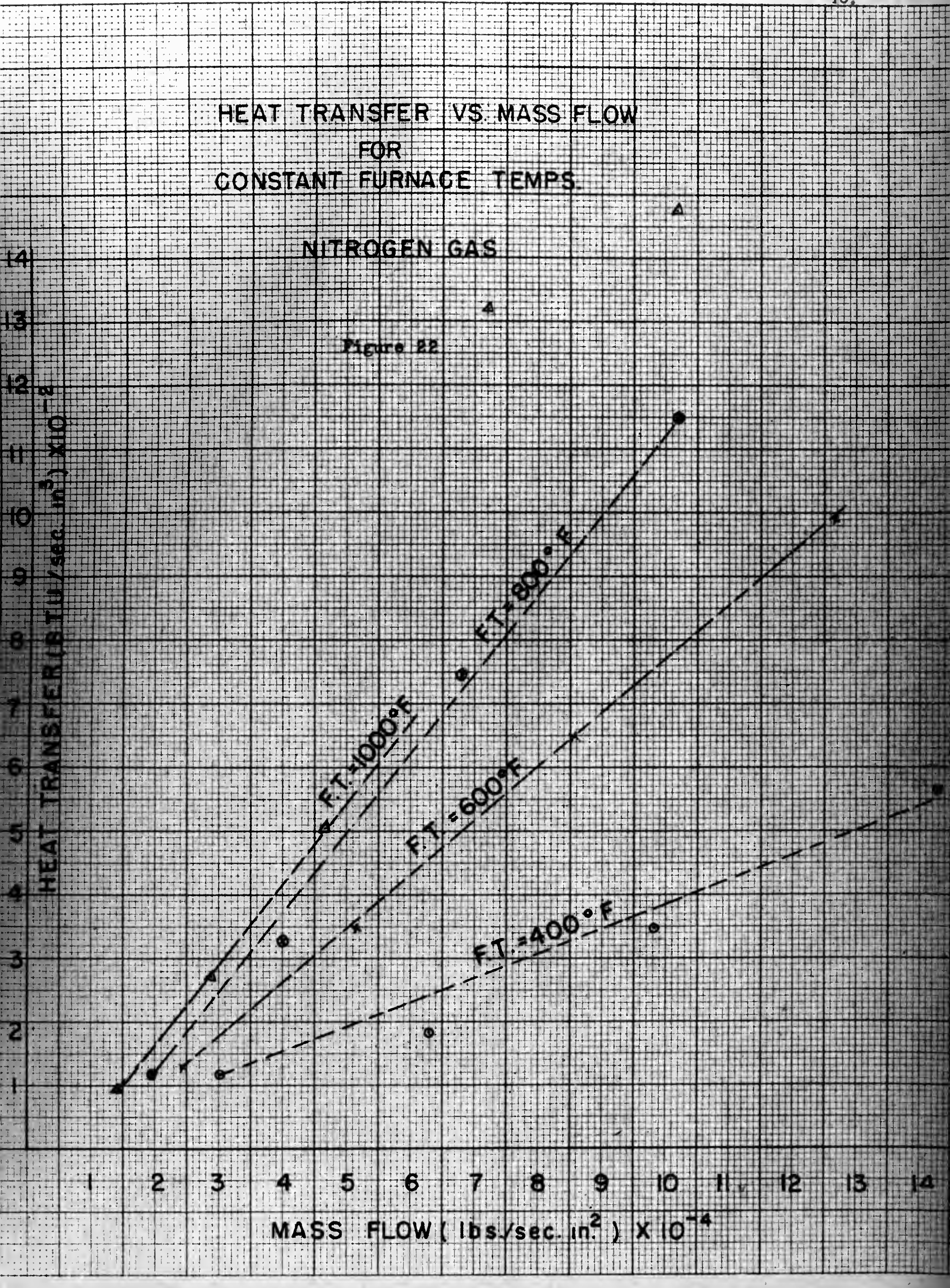
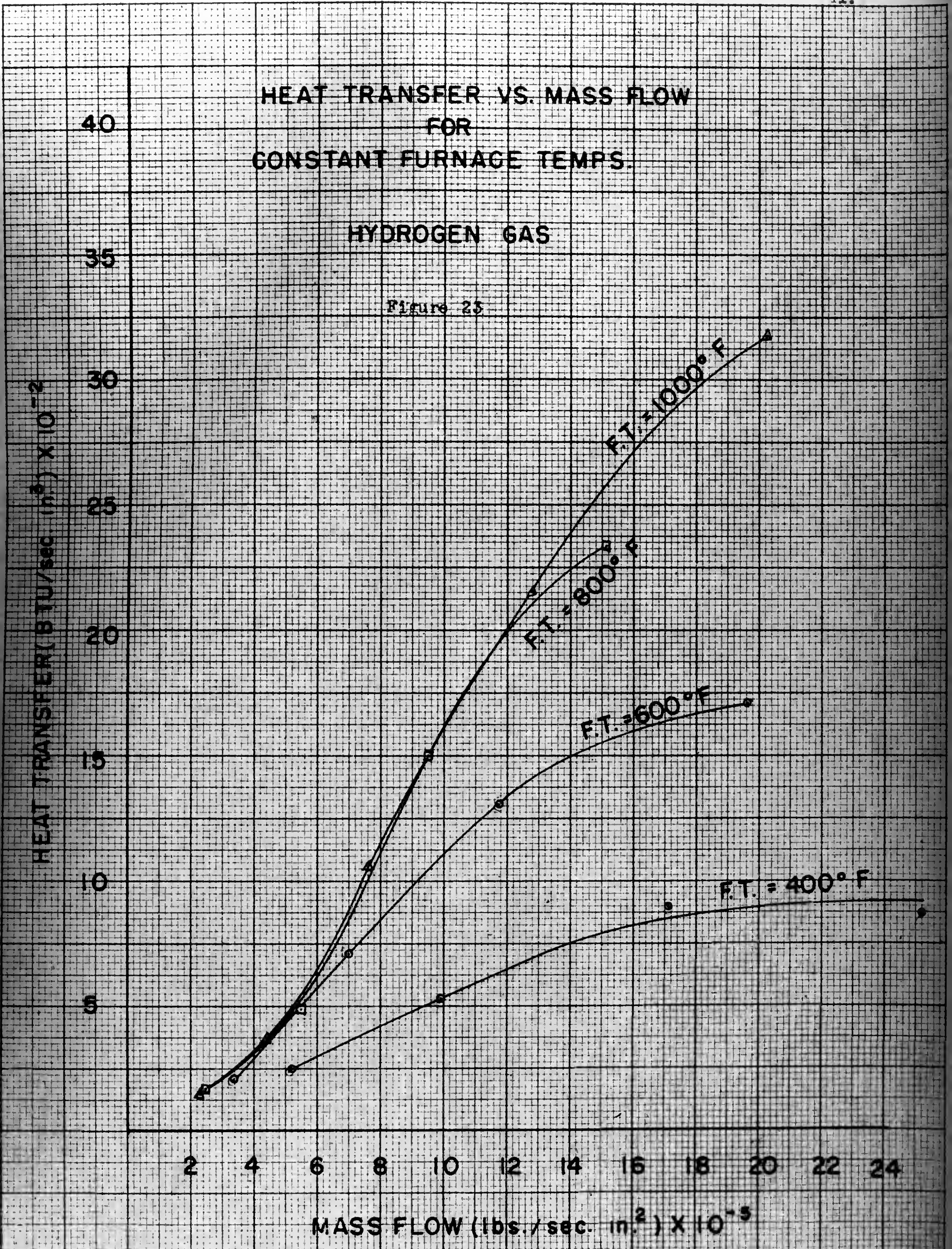

TEMPERATURE GRADIENTS FOR
PRESSURE DROP = 70 PSI
(HYDROGEN GAS)
T (°F)
1000
900
800
700
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
42.9 X 10⁻⁵ lbs/in² sec.
METAL THICKNESS (INCHES)

Figure 19


MASS FLOW VS. PRESSURE DROP
CONSTANT FURNACE TEMPERATURES
(NITROGEN GAS)
Figure 20
PRESSURE DROP (PSI) THROUGH 1" OF METAL
MASS FLOW (lbs/in² sec) X 10⁻⁴
FURNACE TEMPERATURE 1000°F
800°F
600°F
400°F
70°F
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
10
20
30
40
50


MASS FLOW VS. PRESSURE DROP
CONSTANT FURNACE TEMPERATURES
(HYDROGEN GAS)
Figure 21
FURNACE TEMPERATURE 1000°F
800°F
600°F
400°F
70°F
PRESSURE DROP (PSI) THROUGH 1" OF METAL
10
20
30
40
50
0
2
4
6
8
10
12
14
16
18
20
22
24
MASS FLOW (lbs/in^2 sec) X 10^{-5}


HEAT TRANSFER VS MASS FLOW
FOR
CONSTANT FURNACE TEMPS.
NITROGEN GAS
Figure 22
HEAT TRANSFER (B.T.U./sec. in³) X10⁻²
MASS FLOW (lbs./sec. in²) X 10⁻⁴
F.T.=1000°F
F.T.=800°F
F.T.=600°F
F.T.=400°F
1
2
3
4
5
6
7
8
9
10
11
12
13
14


HEAT TRANSFER VS. MASS FLOW
FOR
CONSTANT FURNACE TEMPS.
HYDROGEN GAS
Figure 23
F.T. = 1000° F
F.T. = 800° F
F.T. = 600° F
F.T. = 400° F
HEAT TRANSFER (BTU/sec. in.²) X 10⁻²
MASS FLOW (lbs./sec. in.²) X 10⁻⁵
40
35
30
25
20
15
10
5
2
4
6
8
10
12
14
16
18
20
22
24

CONCLUSIONS

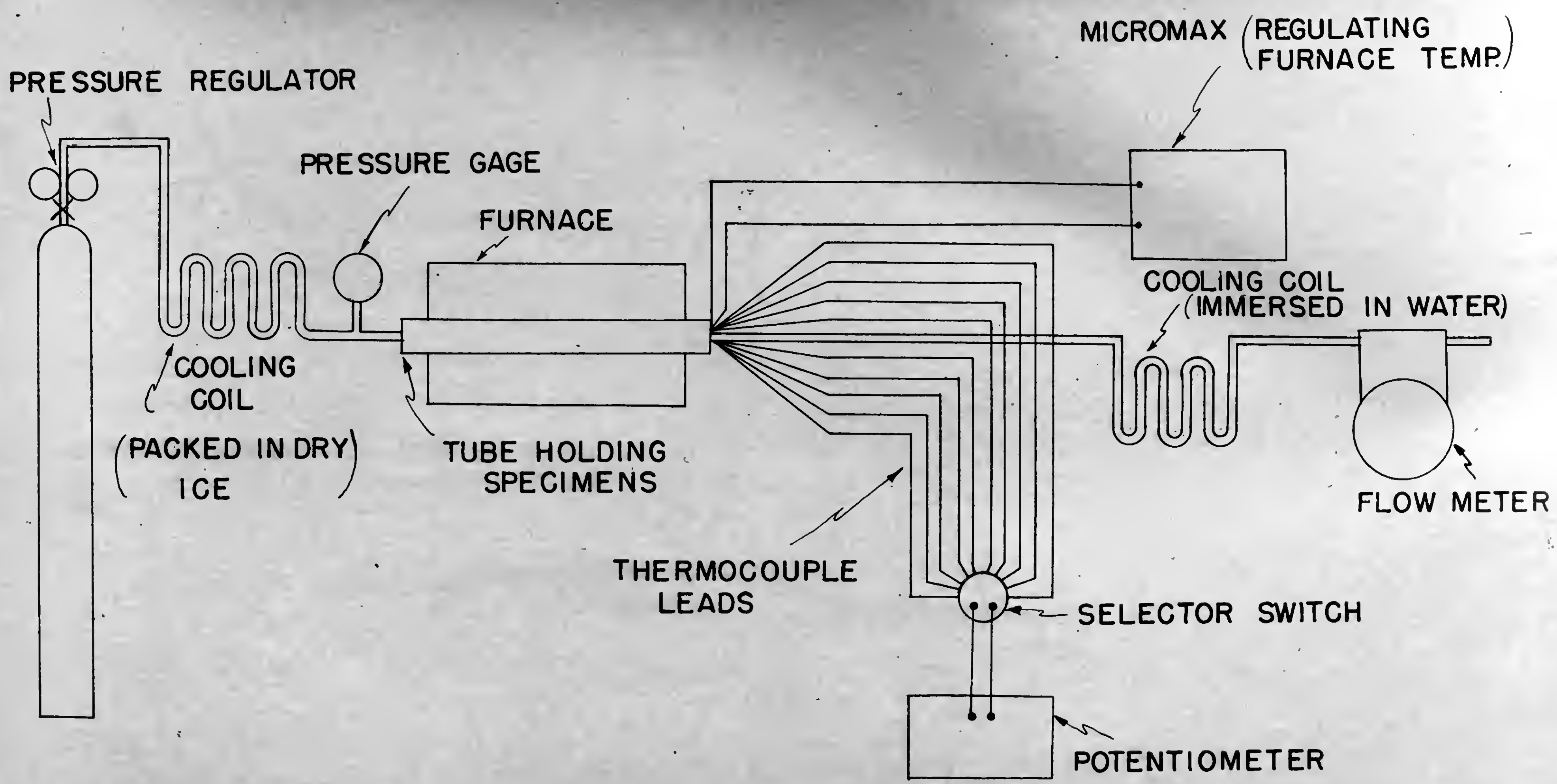
From the results obtained the following conclusions were made:

(1) A cool gas flowing into a heated porous metal very quickly assumes the temperature of the metal.

(2) Heat transfer appears to increase linearly with mass flow up to a certain point above which the results were inconclusive.

(3) The variation of mass flow with pressure drop and temperature change was found to agree with expectations, that is, due to viscosity effects, increasing temperature decreased mass flow and increasing pressure increased mass flow.

(4) External heating is unsatisfactory for obtaining the desired results. It is believed that nearly uniform heating can be achieved by electrical resistance type heating (see Appendix).

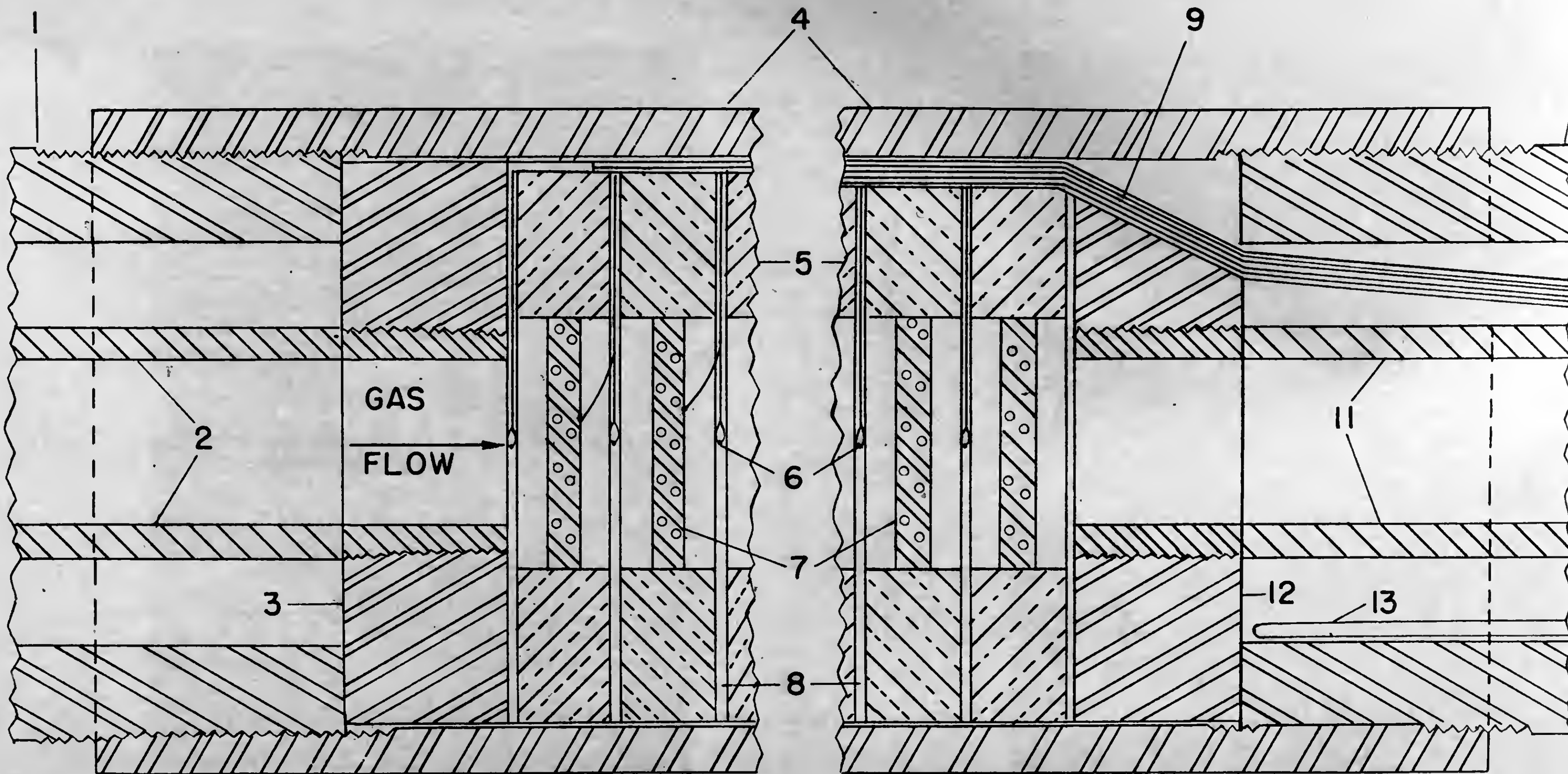


SCHEMATIC DIAGRAM OF APPARATUS

FIG. 24

POROUS METAL PACK

FIG. 25



1 — STEEL TUBE

2 — $\frac{3''}{8}$ ENTRY PIPE

3 — STEEL DISC

4 — STAINLESS STEEL TUBES

5 — BRASS RINGS

6 — THERMOCOUPLES

7 — POROUS METAL SPECIMENS

8 — GARLOCK GASKETS

9 — THERMOCOUPLE LEADS

10 — STEEL TUBE

11 — $\frac{3''}{8}$ DISCHARGE PIPE

12 — STEEL DISC

13 — MICROMAX THERMOCOUPLE

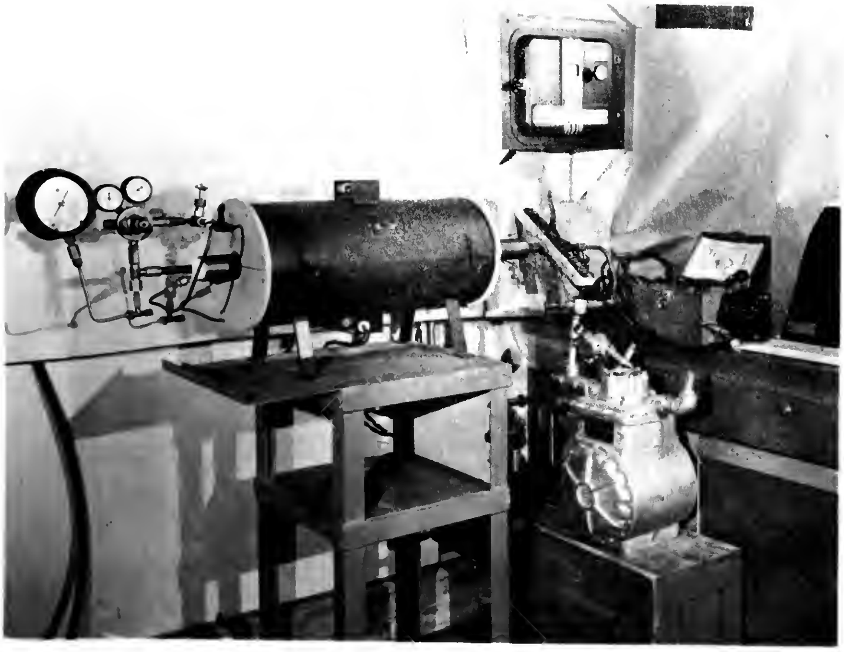


Figure 26
Complete Assembly of Apparatus

Figure 27
Pack Assembly in Open Furnace

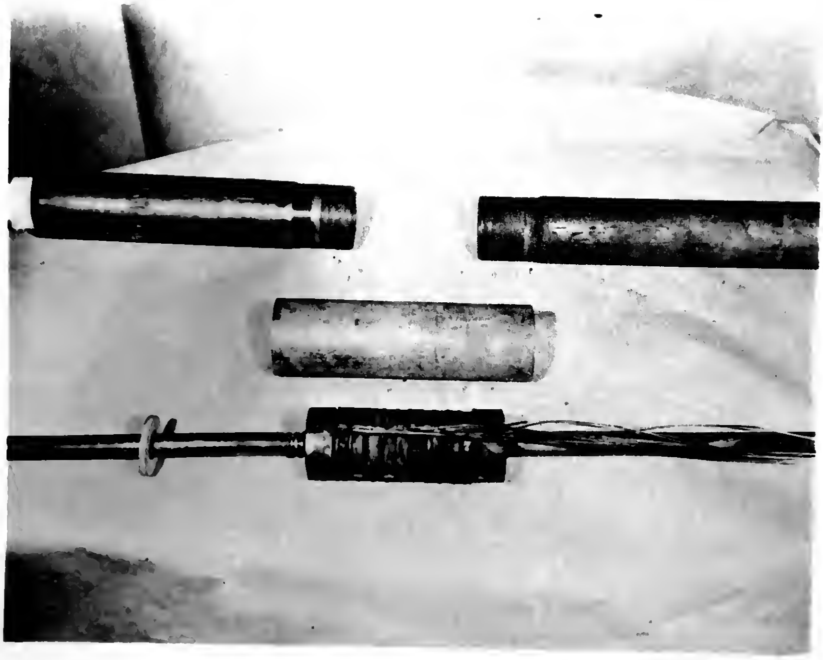


Figure 28
Pack and Containing Tubes

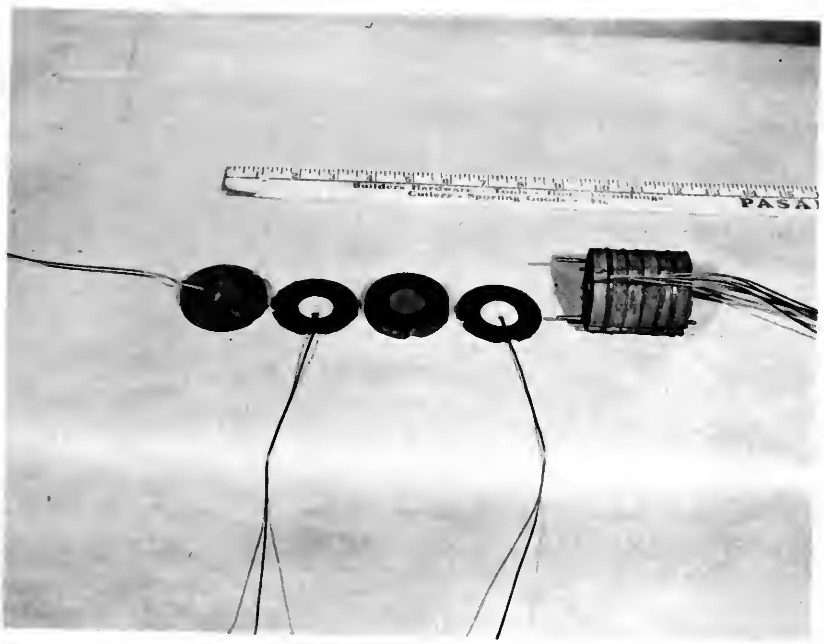


Figure 29
Breakdown of Pack

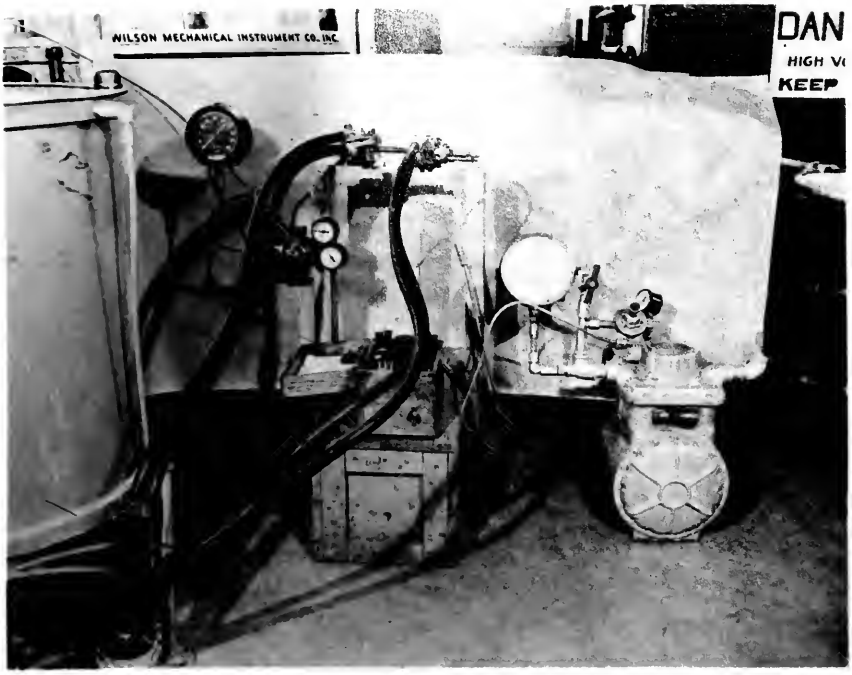


Figure 30
Assembly of Resistance Heating Apparatus

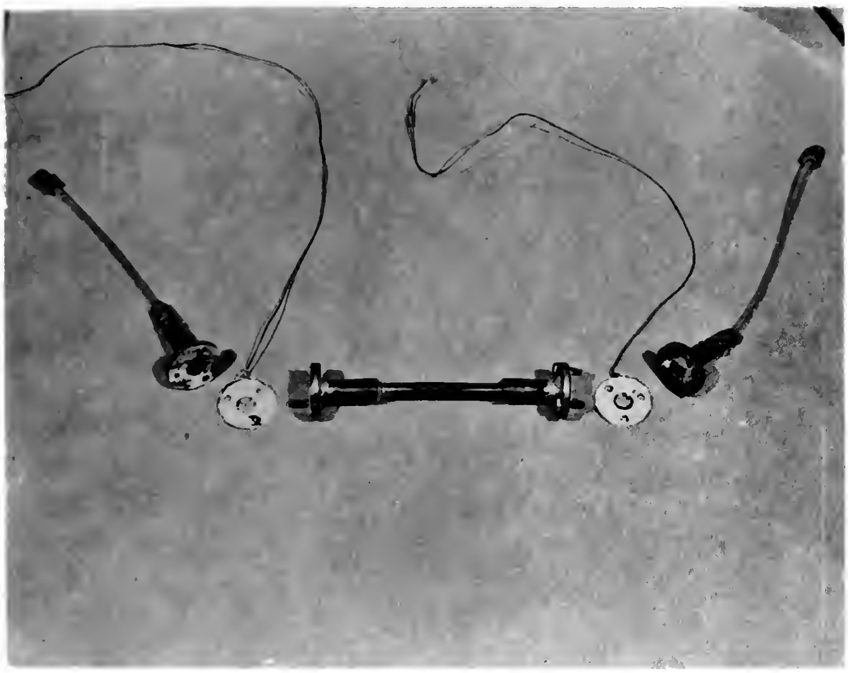


Figure 31
Breakdown of Resistance Heating Assembly

SAMPLE CALCULATIONS

Symbols:

C_p = Specific Heat (For hydrogen is 3.51 BTU/F-lb)

Q = Heat transfer per unit volume per unit time (BTU/in^3-sec)

q = Heat transfer per unit time (BTU/sec)

M = Mass flow rate (lbs/sec)

m = Mass flow rate per unit area (lbs/sec-in^2)

p = Pressure (lbs/in^2)

p_o = Atmospheric pressure = 14.7 lbs/in^2)

T = Temperature (degrees Kelvin)

υ = Volumetric flow rate (cu.ft./sec)

ρ = Density of gas (For hydrogen is 0.00562 lbs/ft^3 at standard pressure and temperature)

T_o = Standard temperature = 273° Kelvin

A = Area of cross section (ins.^{3})

t = thickness (in.)

(A) Mass Flow Calculations

Example: Hydrogen Gas

ρ = 0.00562 lbs/ft^3

p = 14.7 lbs/in^2

T = 24 + 273 = 297°

$\upsilon = \frac{1}{462}$ ft^3/sec

D = 0.75 in.

$$M = \rho \upsilon \frac{T_o}{T} \frac{p}{p_o}$$

$$m = \frac{M}{A} = \frac{\rho \upsilon}{A} \frac{T_o}{T} \frac{p}{p_o}$$

$$A = \frac{\pi}{4}(0.75)^2 = 0.4415 \text{ in}^2$$

$$m = \frac{(0.00562)(273)(14.7)}{(462)(.4415)(297)(14.7)}$$

$$m = 2.53 \times 10^{-5} \text{ lbs/sec-in}^2$$

(B) Heat Transfer Calculations:

Calculations for the heat transfer curves plotted in Figs. 22 and 23 were based upon the heat transferred by the fifth specimen numbered from the inlet end.

$$q = MC_p\,(T_2 - T_1)$$

$$Q = q/At \quad = \frac{m\,C_p\,(T_2 - T_1)}{t}$$

Example:

Hydrogen Gas

$m = 7.59 \times 10^{-5}$ lbs/in^2-sec

$C_p = 3.51$ BTU/lb - $^\circ$F

$T_2 = 820^\circ$F

$T_1 = 780^\circ$F

$t = 0.1$ inches

$$Q = \frac{(7.59)(3.51)(820-780) \times 10^{-5}}{0.1}$$

$$Q = 10.68 \times 10^{-2} \text{ BTU/in}^3\text{-sec}$$

APPENDIX

Discussion of Efforts to Accomplish Uniform Heating of a Specimen by Electrical Resistance Heating

It was determined that the greatest shortcoming of the apparatus used to make the subject study was the external heating, which departed considerably from the desired uniform heating.

Subsequent to most of the preparation of this report an effort was made to accomplish uniform heating by electrical resistance heating. A 47% porous specimen containing 20% iron and 80% nickel was prepared in a modified dumbell shape (Fig. 31). The center section was solid and cylindrical, 1/2 inches in diameter and 4 inches long. The ends were solid and cylindrical 3/4 inches in diameter and each 1 inch long. In order to pass gas axially through the specimen, copper tubing was fitted over and silver soldered to the ends of the specimen. A flanged joint (Fig. 3) was placed in each copper tube to permit the introduction of thermocouples into the incoming and outgoing gas streams. The large specimen ends were connected to the terminals of a variable power source having 100 kva maximum available power. The gas was lead in and out through saran tubing to provide electrical insulation. Approximately 8 kva applied at 25 volts and 320 amperes was found to be adequate to heat the center section of the specimen to a bright cherry red. It was readily seen that while a gain had been made in the efforts to accomplish uniform heating across the center section, the large ends and the heavy copper terminals were drawing heat out of the ends of

the center section causing them to be at a relatively low temperature compared to the cherry red center. Rolling, polishing, and chromium plating were each tried in separate attempts to make the specimen's surface gas tight. Each was found to be inadequate to prevent the escape of gas radially. These complications led to discarding the set-up as a means for making quantitative observations. Therefore, no numerical data were recorded from the observations of this equipment.

It is believed that both of the before mentioned shortcomings of this apparatus can be minimized or eliminated by the use of a hollow cylinder. In this set-up a hollow cylinder would be heated by electrical resistance heating while a gas introduced from the open ends is flowed radially outward and sampled to determine temperatures. The problem of sealing the specimen surface would be eliminated. It is believed that if the tube is made long relative to its metal cross sectional area the flow of heat into the ends and power terminals would be minimized and a reasonable degree of uniform heating would be accomplished. By using a thickness which was small compared to the length of the solid dumbell specimen, described above, a relatively large mass flow could be realized.

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